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Design of a Cryogenic Coolant Inducer

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Design of a Cryogenic Coolant Inducer

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"I certify that I have read and understood the section in the MSc Student Handbook on Cheating and Plagiarism and that all material in this assignment is my own work, except where I have indicated with appropriate references."

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List of acronyms

AM – Additive Manufacture

CAD – Computer Aided Design

CNC – Computer Numerical Control

CMM – Co-ordinate Measurement Machine

CMS – Cryogenic Machining System

CO_2 – Carbon Dioxide

CTE – Coefficient of Thermal Expansion

EBM – Electron Beam Melting

FMEA - Failure Mode and Effect Analysis

HPJAM – High Pressure Jet Assisted Machining

LN_2 – Liquid Nitrogen

MQL – Minimum Quantity Lubrication

PDS – Product Design Specification

PTFE – Polytetrafluoroethylene

RPM – Revolutions per Minute

RPN – Risk Priority Number

Abstract

This thesis details research relating to the design, manufacture and testing of a novel device that can be retrofitted to CNC machining centres to provide a flow of a cryogenic coolant – in this case liquid nitrogen to the cutting zone. A literature survey was undertaken in two parts, the first to review the advantages of using cryogenic coolants and the second to investigate the current state-of-the-art in both academia and industry. A gap was identified for a solution that could be retrofitted onto existing machine tools, avoiding the need for expensive modifications and allowing existing machine tools and tooling to be used. By following an adapted design methodology, requirements were generated into a product design specifications (PDS) and suitable concepts were generated. Through weighted methods it was decided upon an arrangement that used a rotational union as a coupling to guide liquid nitrogen into a shank for through tool cooling. A cryogenic coolant inducer was designed and manufactured. Labyrinth seals were developed to create a rotational union between the rotating central tool shank and the incoming vacuum line of liquid nitrogen.

The initial design was tested on a Bridgeport CNC machining centre. It was found in the first instance that the sealing arrangement was unsatisfactory leading to large leaks that increased proportionally with spindle rotational speed. Through an iterative design and testing process the design of the labyrinth seals was refined to work at higher spindle speeds. An axial impeller was also developed to pump the liquid nitrogen inwards and down towards the cutting tool. The final iteration was used to machine a titanium (Ti-6AL-4V) workpiece. The results were analysed to inform future improvements.

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2 Introduction

Airbus are Europe's biggest consumer of titanium spending £1.2billion per year - 70% is turned into metal chips (swarf). 256 tonnes of titanium is bought for A380 of which only 77 tonnes flies. 24hrs machining, 36 cutting tools (Airbus, 2012). High performance alloys such as, Titanium, Nickel and iron based alloys possess specific properties that include high material strength and hardness at elevated temperatures that make them ideal for applications in aerospace engine structures, marine, nuclear and medical applications (Ezugwu and Wang, 1997). It is these desirable properties that make high performance alloys notoriously difficult to machine (Cowell, 2011). Titanium alloys exhibit properties such as high specific strength, fracture resistance, good corrosion resistance and a relatively low density. The body's natural healing mechanisms do not reject Titanium alloys meaning that they have a high capacity for osseo-integration (Kean, 2010). In industry, Titanium alloys are generally considered to be 'difficult to machine' materials. A high chemical reactivity means that it will form bonds with most cutting tool materials, forming a built-up edge on the cutting tool. Titanium possesses a high toughness which leads to the cut material being wiped across the work piece and not breaking away as distinct chips (Ezugwu and Wang, 1997; Ti and Uns, 2011). This is compounded by its low thermal conductivity causing heat to build up in the cutting zone, leading to high thermal wear of the tool from chip adhesion to the cutting surface (built up edge), micro cracks from thermally induced stress and thermal softening (Rotella *et al.*, 2014).

Water based coolant systems are commonly used to control heat generation in machining. Usually this is used in the form of an emulsion of lubricating oils and additives dissolved into water (Klocke and Eisenblätter, 1998). Flood coolant systems for machine tools require considerable maintenance, consumables and come with associated health risks for workers. To solve these issues companies are looking towards alternative methods of lubricating and cooling during metal cutting. The ideal solution is the total removal of cutting fluids from machining as demonstrated in dry machining. However, the requirements for productivity and tool life make coolant necessary with the machining of Titanium alloys.

Cryogenic machining utilises super cooled liquefied gases to cool the cutting zone during the machining process. This has the advantage of cooling the cutting zone but then evaporating and leaving no residue. The use of cryogenic coolants has several advantages over conventional flood cooling; reduced costs of finished parts compared to conventional techniques being the underlying driver. These cost savings can be achieved by creating a higher quality machining approach, reducing waste, machining time and improving surface quality. Airbus are Europe's largest consumer of

Titanium alloy Ti-6AL-4V spending £1.2billion per year (*Aerospace Manufacturing and Design*, 2015), of which 70% is turned into chips. A small percentage improvement in machining efficiency could potentialy result in big cost savings. This thesis, investigates the design and development of a through tool cryogenic coolant system which can be retrofitted into most machine tools for machining advanced alloys such as titanium alloy Ti-6Al-4V.

A research gap has been identified for a cryogenic machining system that is able to be fitted to an existing machine tool without the need for extensive modifications to the spindle. A retrofit cryogenic machining system would allow manufacturers to adopt a cryogenic cooling approach to their processes on existing machines with minimal modification.

This thesis is organised into 8 chapters. Following from the introduction, chapter 2 sets out the scope of the work, defining the research boundaries.

Chapter 3 presents a literature review in two parts; the first investigates coolants currently used in industry and future coolant developments. Cryogenic coolants and their advantages are identified and compared. The second part focuses on the state-of-the-art available to enable a cryogenically cooled machining process. As a result of the literature review, a research gap is identified.

Chapter 4 sets out the design methodology that will be used to approach the problem. This chapter explains how requirements will be captured and numerically weighted against one another. From these, design concepts are produced in chapter 5

Chapter 5 uses the methodology set out in chapter 4 to generate concepts. These are weighted against one another using numerical methods and the best solution is selected for further development.

Chapter 6 summarises the final iteration 3 design. Chapter 7 discusses the results of the work against the scope and design specification. Chapter 8 presents conclusions and suggested further work.

3 Scope of research

In this chapter the aims and objectives of the research are identified. Moreover, the scope of the research and research boundaries are highlighted.

3.1 Research aims and objectives

The aim of this research is to design, develop and implement a cryogenic cooling system for use in milling operations to deliver liquid nitrogen (LN_2) to the cutting zone. This aim will be pursued through the following objectives:

I. To review the machining of difficult to machine materials. This will focus on the current approaches used in industry and the state of the art.

II. To review state of the art in cryogenic machining.

III. To specify the design for the retrofit cryogenic system. This will be done through the specification of requirements that the design must meet.

IV. To design a cryogenic delivery system that can be retrofitted to a large proportion of machine tools.

V. To manufacture and test a prototype cryogenic retrofit delivery system in a Bridgeport VMC 610 XP machine tool.

VI. To evaluate the final cryogenic system against the original requirements.

3.2 Scope

I. Firstly, the published literature on machining of difficult-to-machine materials are reviewed and investigated to gain an in-depth understanding of the machining specifications and requirements for machining these materials.

II. It will be necessary to review the state-of-the-art in cryogenic machining. This will include standalone and retrofit systems. Academic research setups will be analysed.

III. From the literature review a series of requirements will be generated that the retrofit cryogenic system (CMS) must be able to satisfy. Using a design methodology adapted from Pugh and Pahl & Beitz (Pugh, 1991; Pahl *et al.*, 2007; Cross, 2008) several concepts for a retrofit CMS will be designed that meet the functional specifications. Using the methodology these will be compared against one another and one selected to be used.

IV. Following the design phase, a prototype will be manufactured. Engineering drawings and a bill of materials will be produced. The cryogenic cooling system will be assembled and fitted on to a machining centre for testing.

V. The cryogenic cooling system will be tested on a machine tool in a milling operation. A test procedure will be generated. Qualitative and quantitative data will be gathered during the experimental phase to inform design. This procedure will be iterated until satisfactory results are achieved.

VI. The final design iteration will be evaluated against the specification to establish the degree of success that has been achieved. Conclusions will be drawn and further work will be suggested.

3.3 Research boundaries

The following points are considered beyond the boundaries of this research:

- This research will not compare the machining performance between the developed cryogenic delivery system and other systems – the focus will only be to deliver cryogen to the cutting zone.
- This research will not consider tool changing whilst in the machine volume. This has been implemented successfully in existing flood coolant inducers.
- This research will not analyse, collect data on any tools used, nor use custom tooling.

4 Machining coolants for difficult to machine materials

This chapter details the current state-of-the-art available in cryogenic machining, both in research and industrial applications.

Firstly, the use of coolants in industry with a predominant focus on the most common approach of conventional 'flood' coolant methods is investigated. The drawbacks are discussed with respect to costs, environmental and health factors. Recent cooling and lubrication strategies are identified such as, minimum quantity lubrication (MQL) and cryogenic cooling. Advantages and disadvantages are discussed for each and compared to flood coolants. Secondly, this literature review summarises the state-of-the-art technology available in industry and academia today, retrofit and standalone systems are reviewed. Finally, the findings from the literature review are discussed.

4.1 Materials that are difficult to machine

Shokrani et al. (2013) categorised difficult to machine materials into three distinct categories; hard, ductile and non-homogenous materials. This is shown below in Figure 4-1. Tearing in composites during cutting can lead to unsatisfactory parts, drilling holes in plastics for instance will often melt the surrounding material leaving a poor finish. Hard materials cause high tool wear and usually have a minimum depth of cut. An example would be Titanium, where a hard oxidised upper layer must be broken through to achieve a good surface finish. If the depth of cut is less than the depth of this layer poor machining performance will be achieved.

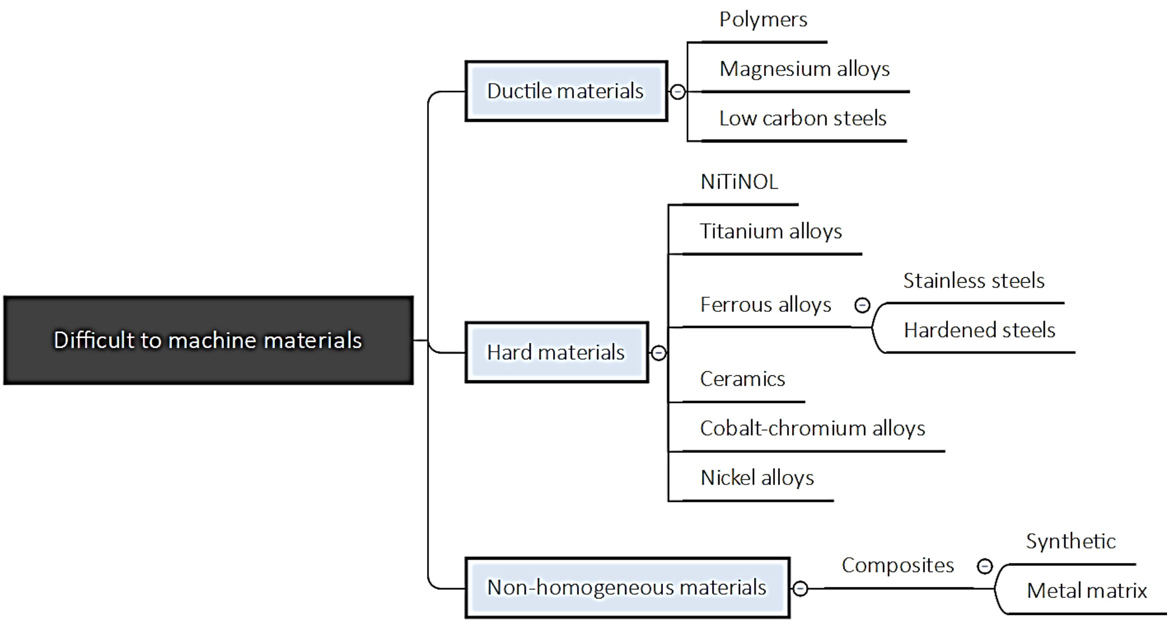


Figure 4-1 – Classification of difficult to machine materials by (Shokrani, 2014)

4.2 Flood coolants

Metal cutting operations create friction between the tool and workpiece, this leads to heat generation (Hong and Zhao, 1999). In industry, the most common way to cool the machining process is to direct a flow of mixture of water mixed with lubricant, known as flood coolant to the workpiece, specifically into the cutting zone (Chiffre L. Belluco, W., 2000; Hendy, Beattie and Burge, 2016).

The cutting operation is subject to a large volume of cooling fluid being applied directly at the workpiece. Flood cooling is the most commonly used machining environment in the metal cutting industry and can account for an estimated 20% of the total machining costs (Klocke and Eisenblätter, 1998). They are used to evacuate chips from the work area, aid in lubricating the cutting interface and remove excess heat from the workpiece and tool. Flood coolants consist of a mix of chemical additives and lubricants mixed in water where a large range of mixtures exist for different materials and industries. The addition of oil or synthetic materials and additives to water has several purposes (Hendy, Beattie and Burge, 2016):

- Lubricates the cutting tool.
- Anti-wear.
- Aid heat removal from the cutting zone.
- Helps prevent corrosion.
- Stops bacterial and mould growth.

Although good at removing heat from the process, the actual cutting zone where the chip is being formed, the temperature can remain unaffected due to the coolant atomising as soon as it begins to penetrate the cutting zone (Dixit, Sarma and Davim, 2012). The design of modern cutting tools has sought to minimise this problem by channelling coolant as close to the cutting zone as possible with through tool cooling, both in standard carbide and insert based tools. Figure 4-2 shows an example of a tool with coolant channels (Sandvik Coromant, 2015).

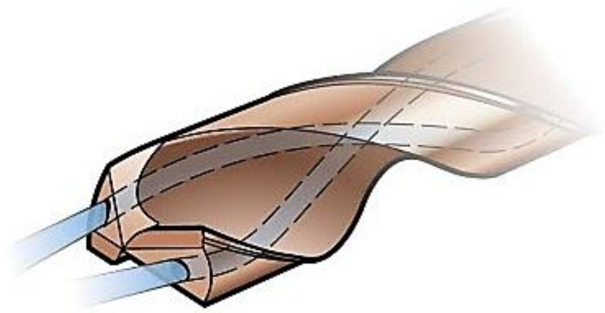


Figure 4-2 – Through tool coolant (Sandvik Coromant, 2015)

Flood coolants are harmful to the environment requiring considerable maintenance and support through their relatively short lifetime which includes filtering, recycling and/or correct disposal (Klocke and Eisenblätter, 1998). The composition of flood coolants make them an ideal setting for the propagation of bacteria and algae, which are harmful to the environment and to the health of operators (Klocke and Eisenblätter, 1998; Shokrani, Dhokia and Newman, 2012; Barber *et al.*, 2014).

A large quantity of coolant is lost to the atmosphere through atomisation and evaporation. Once airborne it can be inhaled by nearby workers. Skin disorders such as dermatitis and respiratory ill health such as asthma, bronchitis and respiratory tract irritation are increasingly common amongst workers working with flood coolant (Soković and Mijanović, 2001). It was found within the employees of Powertrain Limited (HSE, 2007) that a significant proportion were suffering with lung diseases caused by working with coolants.

Often due to the chronic nature of the cases they are not diagnosed until several months after problems develop. This has obvious negative consequences for the individual but also to the business as it can result in reduced worker efficiency and time taken off as sick leave. Prolonged exposure to coolants can also lead to an increased risk of certain cancers such as colon, bladder and lung (Sales *et al.*, 2009).

Metal cutting processes generate a lot of heat and kinetic energy dispersing vapours throughout a factory. These vapours then settle depositing thin film of oils and chemicals in the work environment making regular cleaning necessary further adding to costs (Su *et al.*, 2006). Coolant will be changed at regular intervals throughout the life of a machining centre incurring a large cost to the manufacturer. Soković & Mijanović (2001) describes how rising costs are "…forcing all companies to implement cooling lubrication strategies to suit their own manufacturing structure".

In order to reduce the cost per part manufacturers must budget for the use of coolant (Sreejith and Ngoi, 2000). Running flood coolant systems presents costs in purchasing the equipment and coolant additives needed, maintenance and energy usage (Klocke and Eisenblätter, 1998; Sreejith and Ngoi, 2000; Shokrani, Dhokia and Newman, 2012). A machine tool requires coolant pumps, filters, skimmers and chip removal systems. Further costs are often hidden and harder to quantify. Modern legalisation and environmental laws are important for protecting the environment and the health of workers, forcing the improvement and development of new cooling systems (Pušavec and Kopač, 2011).

To summarise, flood coolants are mostly beneficial to metal cutting. They aid with swarf removal, cool cutting tools increasing tool life and aid with lubricating the process. Flood coolants are presenting an increasingly greater cost to a manufacturer due to tighter legalisation, disposal costs and hidden costs such as health problems. It is therefore desirable to remove the need for flood coolants from a machining process.

4.3 Minimum quantity lubrication

Minimum quantity lubrication (MQL) is a technique whereby an atomiser is used with an oil reservoir to continuously spray oil onto the tool or cutting zone through a stream of high pressure air. The atomisation process is shown in Figure 4-3. The cutting fluid is introduced to a stream of compressed air in a Venturi nozzle. This causes a fine mist to be generated that is directed to the tool. With traditional flood coolant the entire part and tool is constantly bathed in a coolant solution (Dixit, Sarma and Davim, 2012).

MQL has the capability, when installed correctly, to greatly reduce waste and energy usage in a machining process (Park *et al.*, 2014). By eliminating flood coolants in a machining process, costs are reduced by removing the need for the relevant ancillary equipment and processes to condition and process the coolant such as chiller and the disposal costs.

The factory will have a reduced requirement for physical space. Flood coolant does not significantly aid in reducing the friction in the cutting process which is the source of the heat generation (Sharma, Dogra and Suri, 2009). MQL reduces the friction created during the formation of the chip process (Debnath, Reddy and Yi, 2014). Unlike flood cooling the limited quantity of lubricant used is unable to absorb the heat produced from the cutting operation (Kaynak, Lu and Jawahir, 2014). This therefore makes MQL unsuitable for difficult to machine high performance alloys. The fine oil mist generated from MQL also presents a health risk to workers from exposure and inhalation (Kouam *et al.*, 2015).

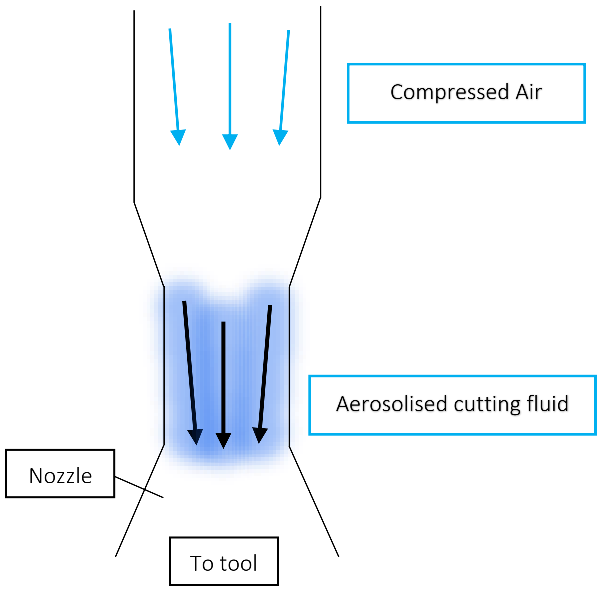


Figure 4-3 – MQL cutting fluid atomisation process

4.4 High pressure jet machining

High pressure jet machining (HPJAM) utilises a high pressure (roughly several hundred bar) injection of cooling and lubricating solution into the work-piece and tool interface (Mazurkiewicz, Kubala and Chow, 1989). The cooling solution contains additives to assist with machining as in flood coolant. This high pressure helps to remove machining chips and to cool the workpiece. Comparatively to flood cooling, HPJAM delivers coolant at a lower flow rate due to the increased delivery pressure. The high pressure also aids with increased chip breaking and machinability (Pusavec, Krajnik and Kopac, 2010). Figure 4-4 below shows a typical HPJAM application used in turning (Sandvik Coromant, 2016).

Figure 4-4 – Coolant jet principle used in HPJAM (Sandvik Coromant, 2016)

When compared to conventional flood coolant it was found that HPJAM led to a 30% decrease in production cost in the machining of Inconel 718. A higher equipment set up cost would quickly be offset by lower costs per part (Pusavec *et al.*, 2010).

HPJAM leaves a residue on part surface and in machines which requires cleaning. This residue and the fluid itself will be disposed of in a similar manner to conventional flood coolants (Chetan *et al.*, 2014).

4.5 Dry machining

Dry machining utilises no cutting fluid. It has become increasingly popular in recent years due to the environmental and legislative concerns with using cutting fluids (Weinert *et al.*, 2004). Having a coolant/lubricant free part or process would be the ultimate 'wish' of any machining company across all materials – from plastics to high performance alloys. The main driver being cost as well as health considerations (Klocke and Eisenblätter, 1998). Typically coolants and lubricants account for 20% of the manufacturing cost of a finished part (Sreejith and Ngoi, 2000).

The use of a coolant also creates a large heat shock to the tool and work piece due to thermal fatigue, potentially leading to cracking and a poor surface finish (Park *et al.*, 2014). It was found in face milling of steels that machining dry offered the best results in terms of surface finish, tool life and power consumption (Vieira, Machado and Ezugwu, 2001). Coolants are also not desirable as parts require a cleaning cycle afterwards to remove any leftovers, this is particularly unwanted with parts used in medical applications.

For roughing operations of Inconel®, nickel based alloys and heat resistant alloys, ceramic end mill cutters work by using a high revolutions per minute (rpm) to get the material to a temperature where it becomes soft – opposite to the low rpm and high torque usually required when machining difficult to machine alloys (Ezugwu and Wang, 1997). This places minimum power, torque and stiffness requirements thus limiting the type of machine tool that the cutters can be used effectively in.

Dry machining presents heat management and chip clearance issues. Compressed air must be used to evacuate machining chips from the cutting interface. Without lubrication from coolants to aid chip formation, tools often require specific coatings therefore increasing cost. When machining difficult to machine materials only high speed milling is efficient with dry machining (Dixit, Sarma and Davim, 2012). Figure 4-5 below shows a Mitsubishi ceramic tool being used in this application (Mitsubishi Advanced Materials & Tools Company, 2016). The high heat generation softens the work material making it easier to remove, this process is only suitable for roughing. The workpiece must undergo a final finishing operation to achieve the required surface finish.

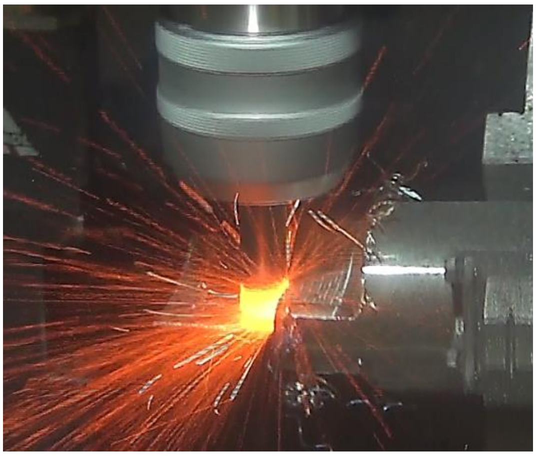


Figure 4-5 – Ceramic cutter use whilst milling a turbine blade (Mitsubishi Advanced Materials & Tools Company, 2016)

4.6 Gas cooled machining

Gas cooled machining utilises chilled and compressed air as the cooling medium. Methods utilising a fluid as the cooling medium require appropriate disposal and cleaning to reduce the environmental impacts of the cutting fluid (Dixit, Sarma and Paulo Davim, 2015). Gas cooled machining directs a nozzle of high pressure cooled gas to the cutting zone, as shown in Figure 4-6 (AMRC, 2015). The cooled gas disperses back into the atmosphere, leaving no residue unlike oil based coolants and therefore poses no health risk to workers through exposure. Gas coolants are comprised of air and a mixture of cooled air with the addition of other gases such as (Rahman *et al.*, 2003). Carbon dioxide liquefies at 218K, a much higher temperature than that of nitrogen (77K) so is also included in this section. In many cases using chilled air directed towards the cutting zone provides greater tool life than compared with traditional coolants (Sharma, Dogra and Suri, 2009).

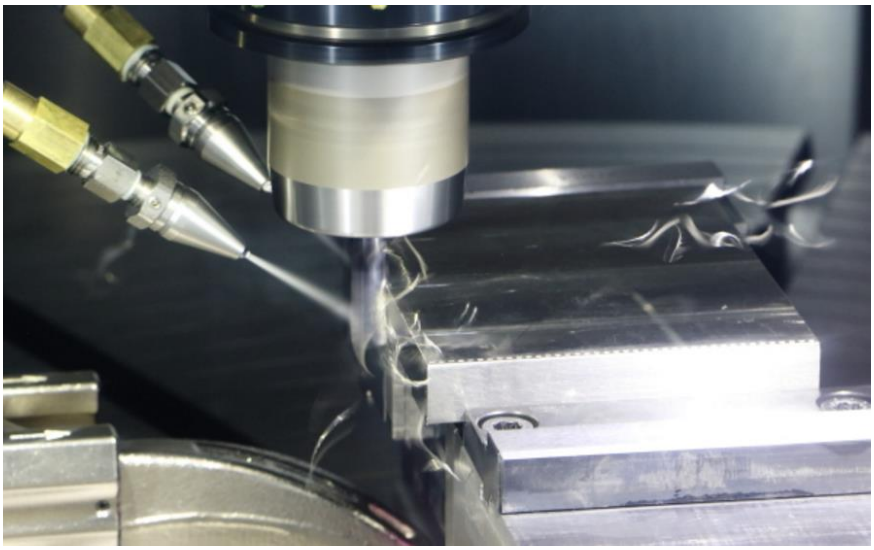


Figure 4-6 – Carbon dioxide cooled machining (AMRC, 2015)

4.7 Cryogenic coolants

Cryogenic fluids are gases at ambient temperature that have been cooled and pressurised to become liquid. Cryogenic machining utilises these super cooled gases to cool the cutting zone during the machining process. Benefits have been shown to be:

- Faster cutting speed
- Increased tool life
- Better surface finish
- No flood coolant
- Lower energy consumption compared to conventional machining methods
- LN_2 can be extracted from the atmosphere. As a waste product from the process it evaporates back in to the atmosphere.

Heat is a large factor in the wear of cutting tools from thermal stresses created from abrasion, shearing and friction (Ghosh, Zurecki and Frey, 2003). Where aggressive speeds and feeds or high spindle speeds are required or if the material is classed as 'difficult to machine' such as titanium or cobalt chrome, this problem is further compounded. The heat generated in the cutting process is drawn away and absorbed by the cryogen evaporating into the atmosphere (Shokrani, Dhokia and Newman, 2012). Traditional oil based coolants have less capacity for absorbing this heat. Cryogenic fluids are therefore applicable for use in difficult to machine material applications (Zhao and Hong, 1992). It is important that the cryogen arrives to the cutting zone in a liquid state to maximise the cooling effect from the phase change to a gaseous state and to prevent an uneven, pulsating flow caused by the boiling of the cryogen (Zurecki, Ghosh and Frey, 2004; Sharma, Dogra and Suri, 2009).

Research has shown (Hong and Ding, 2001; Pušavec and Kopač, 2011; Shokrani, Dhokia and Newman, 2012) the benefits of using cryogenic cooling in machining metals such as Inconel®, titanium alloy and cobalt chrome but also extending to materials such as plastics and composites. There are several mechanisms regarding how using cryogenic coolant offers an advantage and these differ between materials (Shokrani, 2014). In metals, it lowers the critical temperature, where the constituents of an alloy begin to separate, reduces reactivity and aids chip formation (Uehara and Kumagai, 1969). In composites and plastics it can stop tearing and burr formation by forcing the material to go through the glass transition temperature (Bhattacharyya and Horrigan, 1998; Ghosh *et al.*, 2007). Machining solutions taking advantage of cryogenic cooling have begun to come to market over the last five years from companies such as MAG, Starrag and Air Products (Brooks, 2012; *Walter AG*, 2013; MAG, 2016).

4.7.1 Cooling material property changes

Cryogens absorb heat from the cutting tool and workpiece these extreme temperatures change the material properties of both the tool and workpiece materials. Studies have been undertaken on materials using cryogenic fluids to assess what benefits and drawbacks arise when machining different difficult to machine materials, summarised by (Shokrani, 2014) in Figure 4-1, which categorises materials into three categories: hard, ductile and composites that may break into a mixture of both.

Ductile materials such as plastics and soft metals are prone to melting under the friction of cutting and welding onto the surface of the cutting tool (Horrigan *et al.*, 1998; Shokrani, Dhokia and Newman, 2012). Dhokia (2010) utilised LN_2 to freeze soft elastomeric materials to enable machining. In this application, cooling the workpiece material below the glass transition point of the material enables machining of soft elastomers (Kakinuma et al. 2008). Low carbon steels also benefit from cooling, as this can reduce the material toughness making it more brittle allowing for easier material removal (Zhao and Hong, 1992; Hong and Zhao, 1999; Shokrani, Dhokia and Newman, 2012).

Non-homogenous, or composite, materials are prone to tearing and delamination during machining operations. In fibre reinforced materials, the fibres can be pulled out, potentially damaging the tool and even machine tools (Yildiz and Sundaram, 2012). Due to differing hardness values of the materials in a composite, the tool can be suddenly caught by a harder material leading to pre-mature damage or even failure. Use of conventional flood coolant has been shown to even worsen machining through bad surface finish (Yildiz and Sundaram, 2012). Cooling the cutting zone cryogenically causes the material to lose its ductility aiding brittle chip formation. It was concluded by Shokrani (Shokrani *et al.*, 2013) that cryogenic cooling is not beneficial for all materials or conditions.

4.7.2 Cryogenic milling

The use of a cryogenics approach for milling operations has shown clear benefits (Zhao and Hong, 1992; Kaynak, Lu and Jawahir, 2014). Hard materials such as Inconel®, Titanium and super-alloys generate heat at the point of cut. Due to material toughness, slower speeds and feeds must be used for cutting to avoid premature failure of the tool (Zhao and Hong, 1992; Hong and Ding, 2001; Bordin *et al.*, 2015). By cooling the point of cut, tool life is maintained and efficiencies are gained through machining at faster speeds and feeds (Shokrani, 2014).

Park et al., 2014 conducted milling trials on Ti-6Al-4V using different coolant methods that are considered ecologically friendly over conventional oil based flood coolant methods. Figure 4-7 shows the experimental setup used in the investigation. It was found that with a carbide cutting tool, the cutting force decreased with the use of LN_2 (Park *et al.*, 2014). Laser assisted machining (LAM) and minimum quantity lubrication (MQL) are also shown on this diagram. It was concluded that for milling, both MQL and using LN_2 presented a "sustainable solution for energy consumption" (Park *et al.*, 2014),

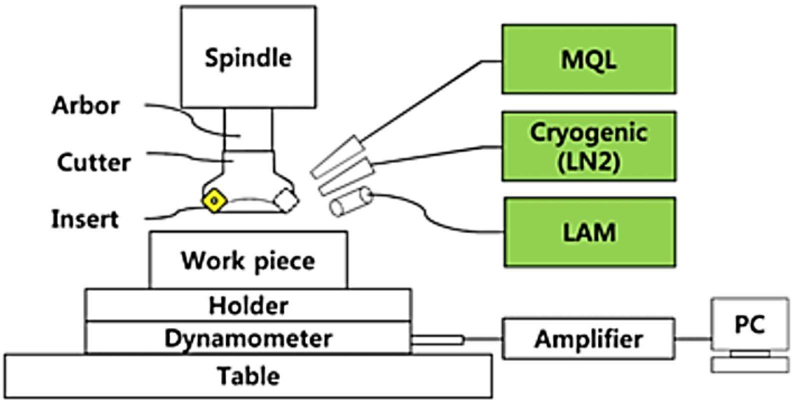


Figure 4-7 – Face milling experiment conducted by (Park *et al.*, 2014)

Shokrani et. al. (2012) developed a cryogenic nozzle to cool both the tool and workpiece simultaneously. It was found that through using LN_2 as the cooling medium in machining Ti-6Al-4V, surface roughness was reduced by 20%. It was concluded that a material removal rate increase of 700% was possible due to higher cutting speeds as a consequence of using the cryogenic machining approach (Shokrani *et al.*, 2013). The experimental lab setup used is shown in Figure 4-8. The Dewar flask can be seen to the right, with a vacuum pipe extending into the vertical milling centre to the nozzle mounted around the spindle. This allows the spindle and bed to move as normal during machining operation. Minimal modifications were required for fitment into the machine.

Figure 4-8 – Previous setup at University of Bath (Shokrani et al. 2012)

Hong (Hong and Ding, 2001) concluded that cryogenic machining when spraying LN_2 in between the chip and chip breaking face yielded the most effective use of LN_2 and could lead to double the cutting speed when compared to conventional flood coolant approaches (Hong and Ding, 2001; Hong, Markus and Jeong, 2001).

Islam, Mia and Dhar (2017) conducted experiments to compare LN_2 to flood coolant when machining a workpiece using an end mill cutter. Both the LN_2 and flood coolant reached the cutting zone through the tool. The flood coolant was channelled to the tool through the spindle. A custom fabricated rotary coolant applicator was used to supply LN_2 to the tool, shown below in Figure 4-9.

Figure 4-9 – Rotary coolant applicator used by Mia (2017)

It was found that using LN_2 to cool the cutting process was more effective than both dry machining and conventional cutting and lubrication fluids when used in end milling of hardened steel. Improvements were observed in a lower cutting force, improved surface finish and reduced cutting energy. It was concluded that using LN_2 to cool the cutting zone is a more sustainable process than flood coolant. The journal article (Islam, Mia and Dhar, 2017) only show a photograph of a nitrogen mist exiting the tool and no photos of the setup being used under rotation. No mention of the utilised spindle speeds are also used. It is therefore believed that this setup suffered from large leaks due to the rotational forces and was employed strictly as a research based setup.

4.7.3 Cryogenic turning

The turning of difficult to machine materials is prone to the same problems as milling; high cutting forces, temperatures leading to short tool life and undesirable surface finishes. There has been a more focused effort on research and development of cryogenic machining applications in turning (Ghosh, Zurecki and Frey, 2003). In comparison to conventional flood coolant, benefits in terms of tool life were observed when turning bearing steel using LN_2 as the coolant medium (Biček *et al.*, 2012). Jerold & Kumar (2013) used LN_2 and CO_2 in the machining of Ti–6Al–4V in a comparative study against flood coolant. It was found that both LN_2 and CO_2 offered a benefit over flood coolant. LN_2 was observed to have the greatest impact upon the cutting temperature. CO_2 showed a better surface finish and lower cutting forces in comparison to LN_2, with better chip control and tool wear (Biček *et al.*, 2012).

Because LN_2 is at 77K when liquid, it has a large capacity to absorb heat through evaporation. This heat absorption potential has been shown to help reduce the strain experienced on the work piece from thermal expansion and contraction caused by high cutting temperatures (Paul, Dhar and Chattopadhyay, 2001; Dhar, Paul and Chattopadhyay, 2002). Hong et al. (2001) proposed a new cooling approach for turning Ti-6AL-4V where a precise jet of LN_2 is directed straight into the cutting zone between the rake face of the tool and the chip itself. This jet acts directly on the chip aiding with its formation and improving breakability. It was also found that the LN_2, which boils instantly into the atmosphere upon contact with the work piece provided a lubricating effect thus reducing the cutting force as shown in Figure 4-10. It was found that using this setup tool life increases by up to 500% (Hong and Ding, 2001).

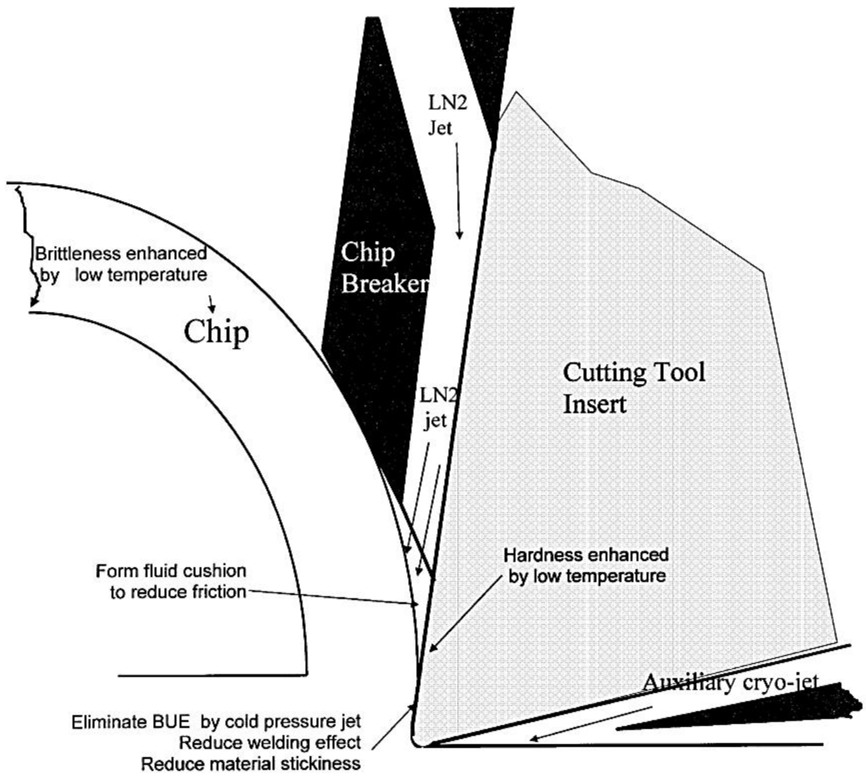


Figure 4-10 – LN_2 Jet directed at the chip (Hong, Markus and Jeong, 2001)

4.8 Summary of coolant approaches for difficult to machine materials

Table 3-1 summarises different machining environments for machining difficult to machine materials.

Table 4-1 - Summary of coolant strategies

Strategy	Cooling medium	Comments
Dry	None.	Desirable for environmental factors. Not always practical due to tool wear, limited application. Only used in roughing operations with difficult to machine materials. (Klocke and Eisenblätter, 1998)
Flood	Water miscible oils with oil and addition of additives to improve lubrication and to stabilise solution.	Most commonly used method in industry. Shows a clear benefit, lubricates cut, clears chips and cools cutting zone. Can be detrimental to environment and health of workers. Expensive in the long run, often costs are hidden (time off sick etc.) (Hong, Markus and Jeong, 2001; Shokrani *et al.*, 2013; Shokrani, Dhokia and Newman, 2014)
HPJAM	Same as flood.	Higher pressure allows less coolant to be used. Same problems arise as coolant additives/cutting oils not eliminated, but are used in lesser quantity. (Pusavec, Krajnik and Kopac, 2010)
MQL	Atomised oil mist sprayed at cutting zone under high pressure.	Helps lubricate the cutting interface to enable better chip formation and decrease flank drag. Unsuitable for difficult to machine materials due to limited ability to soak up heat generation. Oil mist can be harmful to workers (Kouam *et al.*, 2015; Sun *et al.*, 2015).
Gas cooled	Cooled air/ Cooled air + other gases e.g. argon	Leaves no residue, limited ability to clear chips away – cannot be used with drilling etc. (Zurecki, Ghosh and Frey, 2004; Dilip Jerold and Pradeep Kumar, 2012; Shokrani, Dhokia and Newman, 2014)
Cryogenic	LN_2/ carbon dioxide	Large capacity to absorb heat in difficult to machine materials. Leaves no residue – dissipates back into atmosphere. Safe to workers but requires larger investment in specialised equipment. Examples include room oxygen level sensors, gloves for handling cold parts, training and the equipment for storing and delivering cryogen into the machine. (Zhao and Hong, 1992; Hong and Ding, 2001; Hong, 2006; Shokrani *et al.*, 2013; Zhang *et al.*, 2016)

4.9 Commercially available standalone cryogenic machining systems

This section outlines the current state-of-the-art available in industry for cryogenic machining, detailing both lower cost retrofit solutions that allow current equipment to be adapted and standalone purpose built cryogenic machining systems.

Retrofitting a turning process for cryogenic machining is simpler than milling. In turning, the cutting tool does not rotate meaning that the cryogenic delivery system that transports the LN_2 can be positioned very close to the tip of the tool without having to consider any form of rotational coupling. The tool will move relative to the workpiece by small amount, this can be compensated for by having a flexible vacuum pipe, LN_2 is not subject to internal friction caused by the rotation which would heat the LN_2.

Air Products Inc. (Brooks, 2012) are a global company specialising in gases, chemicals and processes for a wide array of applications. Through research, a method of delivering cryogen to the tool tip of a turning tool has been developed (Zurecki, Ghosh and Frey, 2004), known commercially as Ice-Fly®. A double tube system is used whereby LN_2 is also circulated around the outside of the main delivery tube, thus cooling the flow and preventing boiling off. Air Products Inc. are a supplier of gases and have developed the system for use with LN_2 which maintains a cutting zone temperature range between 116K and 277K (Zurecki, Ghosh and Frey, 2004). Figure 4-11 shows the system in use in a turning application (Brooks, 2014). The spray jet of LN_2 can clearly be seen angled at the tool.

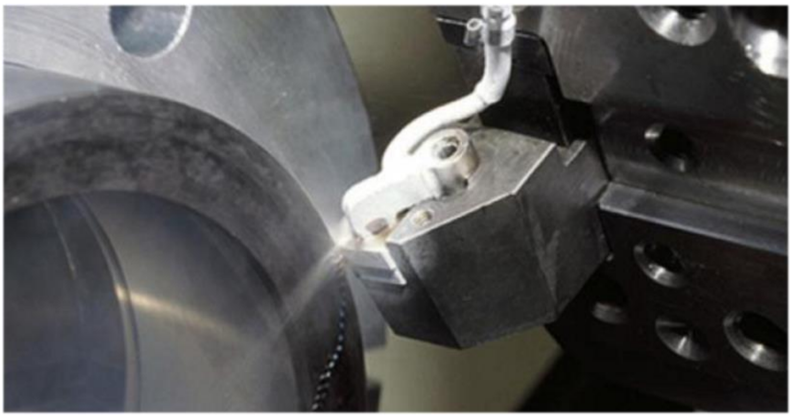


Figure 4-11 – Air Products Ice-Fly® cooling turning tool (Brooks, 2014)

ChilAire™ produce a delivery system for transporting CO_2 to a nozzle directed at the cutting zone (AMRC, 2015), or through a machine spindle that can be specified as a spindle through tool coolant option for milling operations or as a spray jet application that can be adapted to turning or grinding processes. Pressurised liquid CO2 is delivered into cutting zone. It is combined with a high-pressure jet of air where the CO_2 turns into dry ice crystals. As these enter the cutting zone they rapidly absorb the heat from the process through sublimation.

No cutting fluids are required. Significant tool life increases over conventional coolants are claimed (Maurer and Lehming, 2011). Figure 4-12 shows the through tool application of CO_2 in a machining centre. The tool is cooled at the cutter/workpiece from the through body channels and a stream of LN_2 spray can be seen emanating from the tip (Maurer and Lehming, 2011).

Figure 4-12 - Through tool coolant using CO_2 (Maurer and Lehming, 2011)

In 2013, 5ME was created as an output from MAG IAS (5ME, 2013) to commercialise cryogenic coolant technology. MAG have licensed the technology developed originally by Creare, an engineering consultancy (Creare 2016). The system is comprised of several components that work to channel LN_2 to the tool, all controlled by a programmable flow controller for use with the machining centre (5ME, 2015; Stirling W, 2015; Creare, 2016b; MAG, 2016). A Dewar outside the machine provides a self-pressurising source, thus avoiding the need for auxiliary pumps. It is possible to run multiple machines off a single source. The LN_2 is channelled into the machine through vacuum insulated pipes.

Maintaining a liquid state is extremely important - the LN_2 can boil off and convert into a dual phase flow. This is where large gaseous bubbles form in the vacuum pipe, creating a mixture of gaseous and LN_2. 5ME have a patented cooling system that removes pressure generated by this two-phase flow, removing gas and leaving the liquid component. The 5ME spindle system provides an insulated path for LN_2 to reach the tool through the centre. Whilst this can be retrofitted to an existing machine, it is usually specified at the purchase of a new machine due to cost. For this reason, the system is targeted more towards large machining centres that will be used for high value component machining, synonymous with difficult to machine materials and the aerospace and medical industries. A carbide ripper end-mill is shown in Figure 4-13 (MAG, 2016).

By utilising LN_2 as an alternative to traditional cutting fluids, the system is both environmentally friendly and offers (claimed) direct advantages in productivity due to an increased material removal rate (MAG, 2016). Cost savings in running a factory are made from a reduced or eliminated use of other coolants or cutting fluids and oils and their disposal costs (Creare 2015; 5ME 2015).

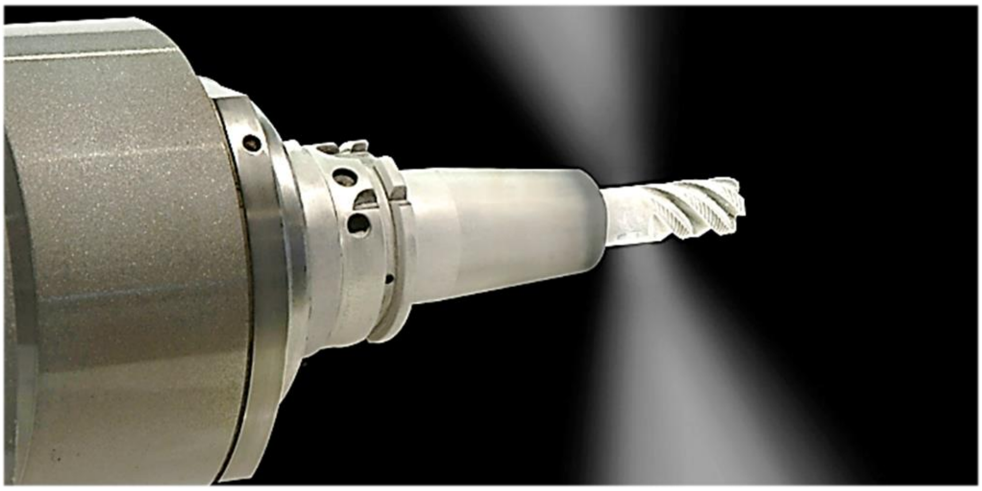


Figure 4-13 - 5ME cryogenic specific tool (5ME, 2015)

The tooling company Walter AG and the machine tool company Starrag have jointly developed a cryogenic 5-axis milling solution that utilises liquefied CO_2 as the cutting medium. The liquid CO_2 is pumped down through the Starrag machining centre through a vacuum insulated pipe where it is forced into the Walter tooling using a spring-loaded taper connection. The tooling provides both separate coolant holes for both cryogen and MQL applications, leading to highly efficient cooling and lubrication of the machining operation. Starrag 5-axis machine tools are targeted at machining difficult to machine materials of where the output is of high value components such as bladed turbine disks and turbine blades. Walter AG has begun supplying tools under the brand name Cryotec which will specifically fit CO_2 cooled Starrag machine tools, Figure 4-14 shows a specific tool.

Figure 4-14 – Walter AG cryogenic specific insert tool (Walter AG 2013)

4.10 Summary of the benefits to using LN_2

The review of literature has shown clear advantages of using LN_2 to cool the cutting zone in the machining of certain materials. These include (but are not limited to) the ability to run at greater feeds and speeds, better surface finish, Increased tool life, less polluting to the environment in comparison to flood coolants.

Titanium is becoming increasingly important material, the F-35 Lightning II combat aircraft produced by Boeing is composed of 25% titanium for which MAGs cryogenic machining system is being used to machine components (Modern Machine Shop, 2011). In the Airbus A380 256 metric tonnes of titanium is purchased but only 77 tonnes are incorporated into the complete airframe, a 70% reduction. Titanium and other difficult to machine materials such as Inconel are being increasingly used for medical implants. Parts are 3D-printed to a near net shape and are then subject to finish machining operations such as drilling holes and tapping.

Machining with LN_2 can offer benefits in productivity have potentially large cost saving implications for a business that are impossible with conventional coolant strategies. During the machining of the wing root airbus set a minimum depth of cut in order to get the desired properties, reducing this minimum depth of cut through cryogenic machining could potentially result in smaller billets being required.

4.11 Discussion and identification of research gaps

A thorough literature review has been undertaken, the first to summarise how coolants are used in subtractive machining processes and the second to assess the current state-of-the-art available in industry today. It has been shown that conventional oil based flood coolant is a significant contributor to the cost of producing a finished part due to cleaning, fluid maintenance, supporting equipment and disposal costs (Klocke and Eisenblätter, 1998). Other problems, such as the effects on the health of operators are less well known but have clearly been shown to be an inherent risk, even when managed properly (HSE, 2007). This is a big problem for manufacturers not only from a monetary point of view but also for complying with increasingly tighter health and safety guidelines. Furthermore, when machining difficult to machine materials, in many cases flood coolant has been concluded as unsuitable (Pušavec and Kopač, 2011; Pusavec *et al.*, 2011; Simeone, Woolley and Rahimifard, 2015). LN_2 has been shown to be a viable alternative for use with difficult to machine materials, classified in Figure 4-1 by Shokrani (2013). The metals classified suffer from excessive heat generation at the cutting zone leading to short tool life, poor part surface finish and high cutting forces. LN_2 can absorb this heat generation through a phase state change to gaseous simply evaporating into the air.

The review of current cryogenic machining technology revealed several approaches all heavily dependent upon the level of investment that a company is willing to make. Retrofitting an experimental setup to a machine utilising a spray nozzle presents a low-cost option, but is only applicable to turning. To machine complex parts on a 5-axis milling centre, a greater investment is required in a standalone system or a costly retrofit. Retrofitting a machining centre with cryogenic through spindle coolant can cost up to $250,000 (Stirling W, 2015). The vast majority of machine shops within the UK are small, containing less than 10 machines (Stirling W, 2015). This means that the high cost of converting these machines must be justified by high value machining applications, such as the machining of high value aircraft components as is done with the 5ME system (MAG, 2016).

Retrofitting cryogenic to a turning operation is comparatively a simpler task than milling since it is the workpiece that rotates and not the cutting tool. This problem has been solved and products exist on the market such as the Ice-Fly® system (Brooks, 2014).

To retrofit a cryogenic cooling system to a machine tool is a costly proposition due to the large amount of modifications that will be required including modification or changing of the spindle.

At present a manufacturer wishing to implement cryogenic machining has limited options when considering a milling process. A retrofit solution such as the Ice-Fly® system can be fitted to the bed or quill of a machine tool to spray cryogen at the cutting zone. Whilst having a far lower price entry point when compared to a standalone machine, this system will limit what manufacturers are capable of machining. . The LN_2 is vented to atmosphere before reaching the cutting zone, as opposed to at the point of cut with a through tool coolant solution such as with MAG machine tools. Tool paths will all have to be manually checked for collisions with the nozzles which must be mounted as close as possible to the cutting zone, meaning that coolant will not reach in to pocketed features or holes, not cooling the process or clearing away metal cutting chips. MAG do offer a retrofit solution however this requires extensive modification to the machine spindle. Sirling (2015) argued that commercially, it is more cost effective to purchase new machining centres with factory installed options for cryogenic coolant.

A research gap has therefore been identified for a cryogenic machining system that is able to be fitted to an existing machine tool without the need for extensive modifications to the spindle, but that can deliver a flow of LN_2 to the cutting zone during drilling. A retrofit cryogenic machining system would allow manufacturers to adopt a cryogenic cooling approach to their processes on existing machines with minimal modification.

5 Methodology for design of a retrofit Cryogenic System for machine tools

This chapter introduces the design methodology for the design of a retrofit cryogenic delivery system for machine tools. It utilises design methodology adapted from Pugh (1991) and Pahl & Beitz (Cross, 2008).

A product design specification (PDS) is formed. This is a prerequisite to the design work which encompasses a detailed requirements list that the final solution must satisfy. Requirements fall into two categories of (i) desirable and (ii) essential to the function of the product. It is of critical importance that the PDS encompasses everything about the product from an early stage, before any initial concept work or engineering calculations begun. Through numerical weighting against success criteria established in the PDS, a concept will be selected for further development.

5.1 Design methodology

Pugh (1991) broke the design process down into five distinct stages prior to release to market. These form the basic structure of this work.

(i) **Analysis of the problem** – this has been defined within the scope and from the discussion of the literature. This will be a statement addressing the problem that the design is meant to overcome.

(ii) **Product Design Specification (PDS)** – From knowledge gained from market analysis, or 'the problem' comes the development of a PDS. This is an in-depth list of attributes that the final product must meet. The PDS encompasses everything that the final product must have – not just engineering design quantification but also aspects including ergonomics, cost, environment etc. The PDS will represent the vision for the product in the individuals or the company's philosophy. The output will be a series of requirements, some essential others desirable. Through weighting these requirements in the design stage, a concept can be selected. A PDS will be created as explained in detail in chapter 5.

(iii) **Conceptual design** – The generation of potential concepts that satisfy the PDS. The concepts are analysed and weighted against one another. Conceptual designs will be sketched out in chapter 5 and weighted against each other to select the most appropriate.

(iv) **Detail design** – The technical solution is created. All technical documentation detailing manufacture and assembly are explained in chapters 5 and 6.

(v) **Iterative manufacture and testing** – The design is iterated through a process of manufacturing and testing. New parts or features are developed to improve upon satisfying the requirements.

5.2 Functional design

Functional design principles will be applied, also known as the ‘black box’ model (Pugh, 1991; Cross, 2008). Functional design creates a boundary around the problem and places a demand upon inputs and outputs that are to be achieved. Shown in Figure 5-1, the boundary separates inputs and outputs – this is where the ‘solution’ is created. The input is LN_2 in a vacuum insulated static line, the output being a flow to the cutting zone. The ‘black box’ is the method or mechanical design that enables this.

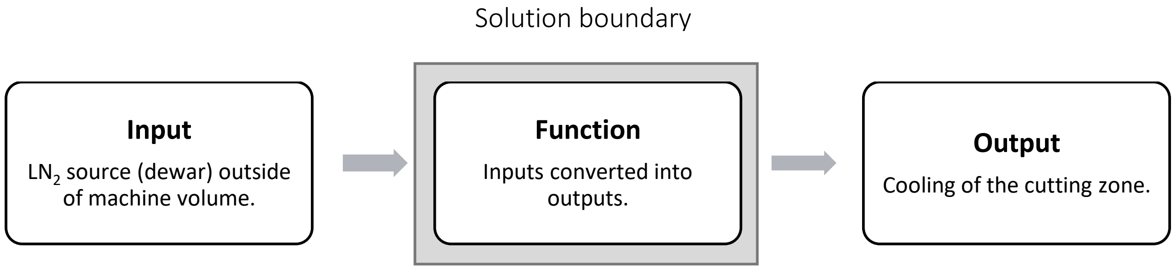


Figure 5-1 - Black box function model (Pugh, 1991)

5.3 Evaluating designs

The design process will be used to generate a range of concepts. A weighted method will be used to assess and select the most appropriate concept to take forward for development. Proposed designs will be checked against the PDS to evaluate the objectives that the design must satisfy. In this research, a weighted objectives method will be used to assess and compare between different concepts designs. It will be important to include non-mechanical criteria such as safety and usability.

The objectives that will be established in chapter 5. Ranking the requirements through order of importance will allow numerical weights to be assigned. A baseline concept is selected and set as the standard, denoted by an ‘S’ in each criterion point. Objectives are considered against each other and assigned a ‘+’ or ‘- ‘respectively if they exceed or fall lower than the selected standard. Table 5-1 shows the rank ordering process that will be used to quantify objectives. The total scores are summed to establish the most suitable concept.

Table 5-1 - Pugh concept selection matrix template

Pugh Concept Selection Matrix	Weighting	Concept 1	Concept 2
Criteria 1			
Criteria 2			
Total +			
Total -			
Total Score			
Weighted Total +			
Weighted Total -			
Weighted Score			

Parameters must be correlated into objectives or statements that can be quantitatively evaluated.

5.4 Materials selection

Materials selection is critical to the performance of an individual components and so the assembled product. Mechanical properties must be considered when designing components to fulfil a function. CES selector will be used to aid this process, developed from the work of Ashby, (1992).

Both cost and physical properties will be evaluated when selecting materials to manufacture the parts. Material properties are listen in Appendix I.

5.5 Testing and design validation

The design will be validated through testing on a CNC machining centre. As defined from the literature, the design must show a clear advantage when compared to the current state-of-the-art from a technological or commercial standpoint.

5.6 Selected methodology summary & flowchart

The final methodology to be used in the design of a cryogenic machining system has been adapted from Pugh and Pahl and Beitz (Pugh, 1991; Pahl *et al.*, 2007; Cross, 2008; Kannengiesser and Gero, 2015). This is shown Figure 5-2.

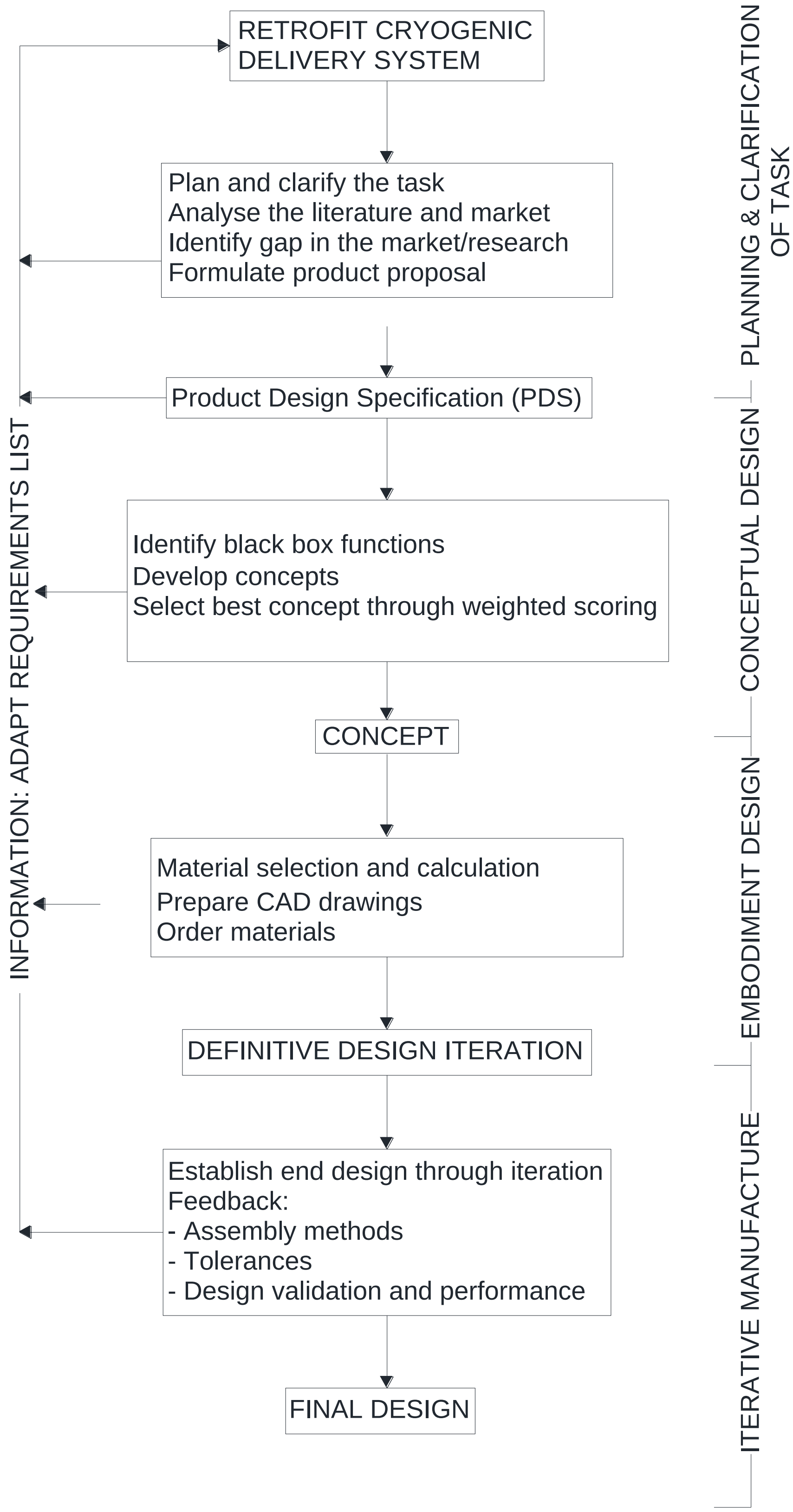


Figure 5-2 – Adapted Pahl & Beitz design process model (Pahl *et al.*, 2007)

6 Design of a retrofit cryogenic machining system

In this chapter, the methodology detailed in chapter 5 is used to design a retrofit cryogenic inducer for use in machining centres. All design work and drawing presented are the work of the author. The presence of cutting chips, heat generation, high energy resonances and lubricating or cooling fluids places a strenuous demand on mechanical seals and other moving components. It shall therefore be a requirement that the developed design can operate under these conditions without excessive wear or servicing requirements. Technical safety requirements of machining centres are set out in BS EN 12417 (BSI, 2001).

Functional requirements are expanded into specifications in the PDS. A black box methodology is used to establish functions of mechanical components. Concepts are generated which are weighted against each one another against satisfying the requirements.

All of the design work detailed in this chapter is the work of the author unless otherwise stated.

6.1 Product design specification

The PDS for this research was developed based on the findings from the literature and industrial requirements as shown in Table 6-1. The PDS is a list of requirements separated into wishes and demands. These are weighted for use in assessing and identifying the most suitable design concept.

Table 6-1 - Product Design Specification Sheet (PDS)

No.	D/W	Wt	Attribute
Mechanical properties			
1.1	D	5	Delivers LN_2 to the cutting zone of the tool and workpiece at machining speeds.
1.2	D	4	Able to be retrofitted to a large majority of machining centres.
1.3	D	5	Able to withstand the fluid flow at 77K from LN_2.
1.4	D	5	Transmits sufficient force to machine difficult to machine materials.
1.5	D	5	Does not suffer any undue vibrational issues through the effective cutting spindle rotational speeds, in a range between 1000-10,000 rpm.
1.6	W	3	Must be able to work with existing tools so that a machine shop does not have to upgrade their tool suite.
1.7	W	3	Any mechanical surfaces that are subject to wear should be designed in such a way that they are self-adjusting or are serviceable.
1.8	D	4	The LN_2 should be at a sufficient pressure to clear chip and machining debris when it arrives at the cutting zone.
1.9	W	3	Other cutting fluids or lubricants should be able to be used in conjunction with the design. For example, the machine may the capacity to also use flood coolant for different parts.
1.10	D	4	There should be no leaks in the system. If this is not possible then the leak rate of LN_2 should be low enough to not impact the cutting process.
1.11	D	5	Design should be easy to control the flow rate and to switch on or off.
1.12	W	4	Mechanical tolerances must be considered throughout and must be achievable through any proposed manufacturing route, not a bespoke one-off process.
1.13	W	3	Can be easily taken in and out of a machine tool with minimal tools and no complex calibration/alignment.
Assembly & Servicing			
2.1	D	4	System should be designed for easy assembly and disassembly.
2.2	W	4	Design should be designed so that mechanically wearing surfaces do not alter performance to an unacceptable level, if this is unavoidable a replacement/service lifespan should be proposed.
Economical			
3.1	D	5	Should work on an economically viable feed quantity of LN_2 that presents an advantage against a competing machining solution such as flood coolant.
Human factors & usability			
4.1	D	4	Should be easy to use and handle including loading/unloading from a machining centre.
4.2	W	3	The mass of the design should be within manual handling safe limits as defined by HSE.
Safety			
5.2	D	5	If a crash occurs during a machining operation there must be a cut off that stops LN_2 venting into the work place.
5.3	D	4	LN_2 flow must be sufficiently low to not alter the ambient work place gas mixture ratios to an unsafe or uncomfortable level.

Figure 6-1 shows an objectives tree diagram for the requirements and how they break down into sub objectives.

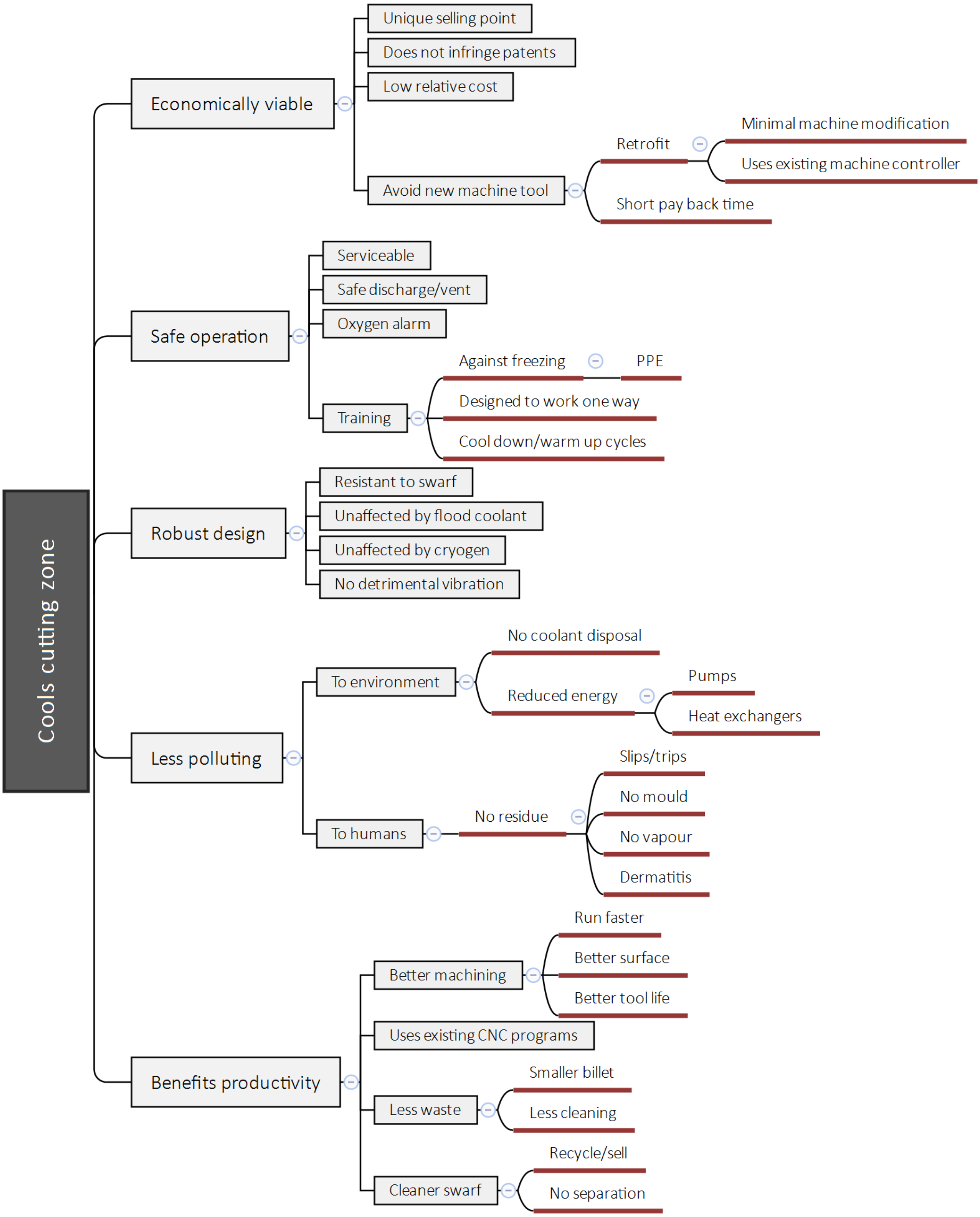


Figure 6-1 - Objectives tree

6.2 Conceptual design

This section details the initial concept designs. The product requirements are identified using a PDS detailed in Table 6-1. The design methodology detailed in chapter 4 is followed. Using a weighted method, the most suitable concept is selected.

I. Requirements structure

Table 6-1 lists the design requirements, both wishes and demands. Demands are required for the underlying function; failure to satisfy any of these is a failed concept. Extracting the fundamental problem through requirements allows the function to be established. From the PDS and Table 6-1, the problem can be phrased as: *A method of delivering a flow of LN_2 to the cutting zone of a milling machine that can be retrofitted with as little modification as possible to existing machining centres, designed to deliver a flow of LN_2 to the point of contact between tool and work piece.*

II. Designing for functional requirements

Three pathways for the LN_2 to reach the cutting zone have been identified:

- Through the spindle into the tool.
- Through an external vacuum insulated pipe into the tool via a rotary union.
- Through an external nozzle/outlet sprayed directly at the cutting zone.

The solution boundary for the design in this work is set as the machine volume, shown below in Figure 6-2.

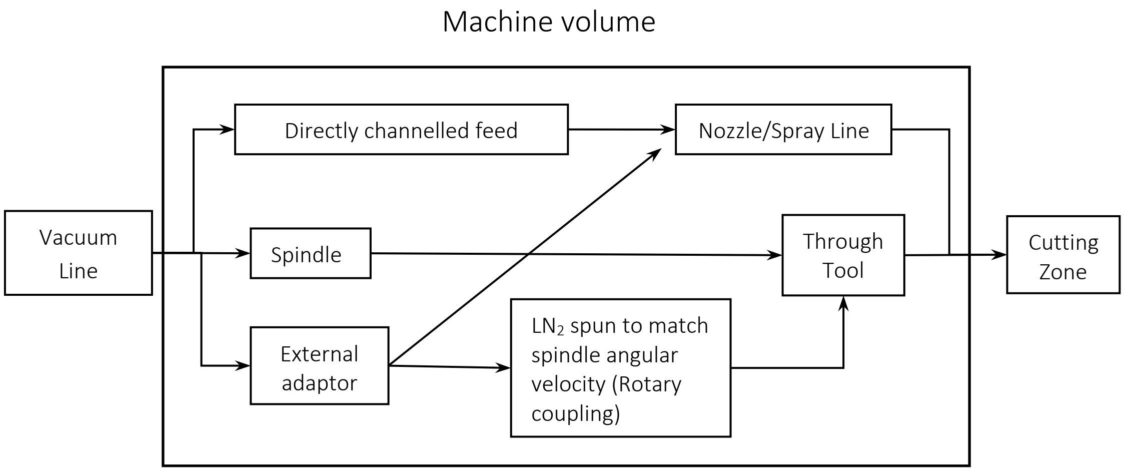


Figure 6-2 - Function model of Cryogenic machining

The function of a cryogenic machining system is to deliver a static line of LN_2 into the machine volume to the tool and workpiece interface (cutting zone). The three pathways are described below and developed into concept variants. This section analyses the functions within the solution boundaries. The purpose is to identify mechanical components that could be designed to solve the problem. At the intersections, the functions are identified. It is a common practice in industry to feed cables to retrofit equipment such as a $4^{th}/5^{th}$ axis for instance through the bulkhead wall. A flexible vacuum insulated pipe can flex and move with the spindle and bed.

Through Spindle - Retrofitting a machine tool to channel a flow of LN_2 down through the spindle will require significant modification. Whilst the research has shown that this is beneficial for the machining of very high value low volume parts in high end factories such as those at Lockheed Martin (*Aerospace Manufacturing and Design*, 2015), the requirement is for a solution that can be retrofitted into existing machine tools with the minimum of modification whilst limiting downtime. This option has been analysed in the literature in section 3.7 but will not be taken any further as a design.

Directly channelled feed line to a nozzle or pipe – A vacuum insulated pipe would provide LN_2 to the cutting zone by spraying the area with a nozzle. Figure 6-3 below shows a HAAS machining high pressure coolant nozzles mounted directly on a common rail angled towards the tool. The nozzles can be repositioned as required, but are not automated and require manual adjusting.

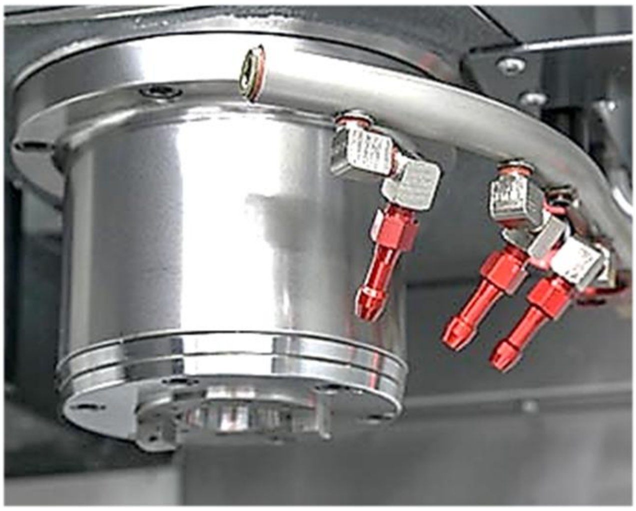


Figure 6-3 – Spray nozzle attached to spindle (HAAS, 2015)

Inducer concept – As identified in the literature review in chapter 3, rotary couplings known as inducers are available for use with flood coolant equipped machines. These offer the benefits of through tool coolant delivery and chip clearing potential without the need to invest in capital equipment. These enable through tool flood coolant to be retrofitted onto existing machining centres. An example is shown in Figure 6-4.

Figure 6-4 – Coolant inducer (BIG Daishowa, no date)

6.3 Concept variants

Through the design activity defined in chapter 4 four strategies have been identified for channelling LN_2 to the cutting zone, these are detailed below.

I. Concept 1 – Direct spray line, spindle mounted

A vacuum insulated flexible line would output to one or more spray nozzles. These nozzles would spray LN_2 directly at the cutting zone. They can be mounted on the spindle or on the bed of the machine. The controlled coolant on and off commands could use the same machine M function, thus allowing for a lower cost retrofit. This concept could potentially be retrofitted to milling, turning and grinding machines. The nozzle(s) would have to be in close proximity to the work piece to provide a stream of LN_2 to the cutting interface and not nitrogen gas. These nozzles could interfere with the tool changing depending on how much physical space is occupied. Toolpaths may also be limited due to the risk of the nozzles interfering with the workpiece or machine. This concept will only be viable for limited tools and parts. A schematic for the concept is shown below in Figure 6-5.

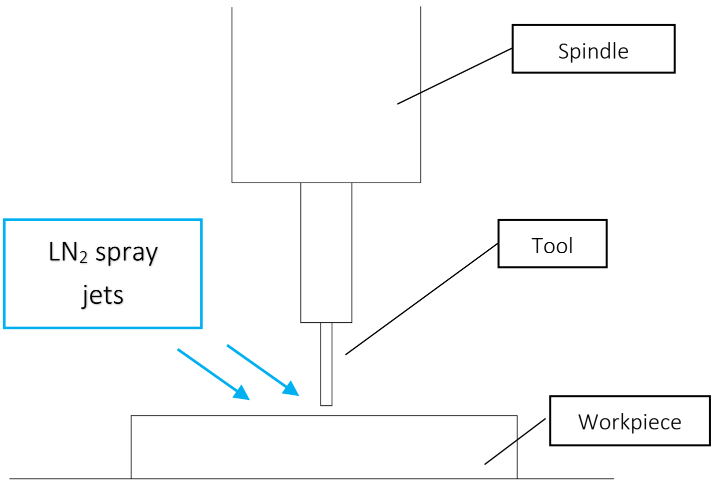


Figure 6-5 – LN_2 Spray jet concept

II. Concept 2 – Cooling pickup rig – hybrid solution

A ring of spray nozzles mounted at the end of a cryogenic flexi hose in a dock on the machine bed. Through a modified movement cycle in the machining program, the z axis picks up/sets down the rig. The pickup rig is shown below in Figure 6-6. The original flood coolant systems could be kept installed on the machines for working with materials where these are required. Through mounting/dismounting of the coolant device the machining centre would be capable of switching between cooling and lubrication strategies. For a small machine shop that had a limited number of machines, this would be of great benefit, keeping manufacturing routes flexible. This solution is potentially physically large and may interfere with tool changing and machining paths – therefore it will only be viable for a limited range of tools and cutting operations – hole drilling and pocketed features will not be possible.

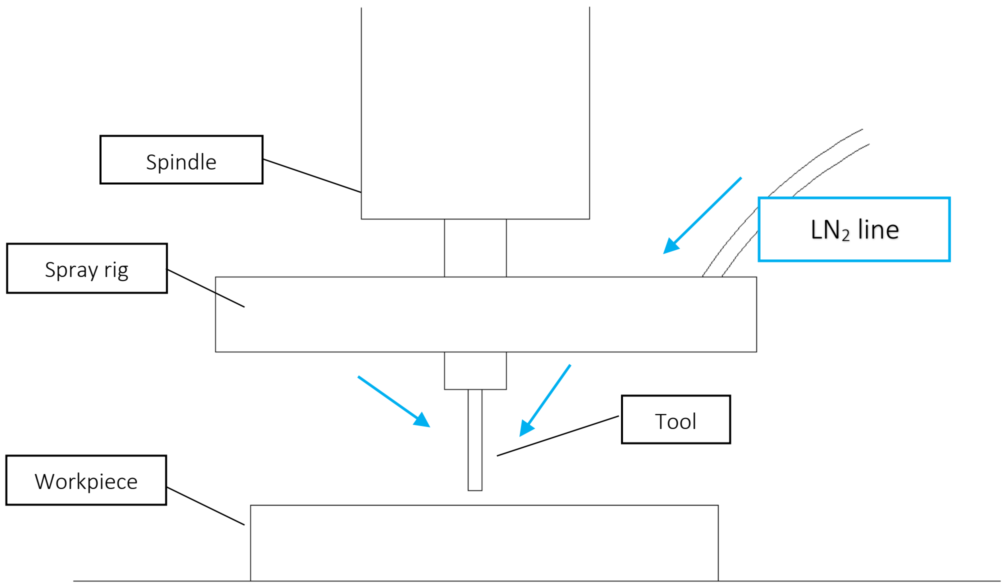


Figure 6-6 - LN_2 spray rig mounted on spindle

III. Concept 3 – Cryogenic coolant inducer with through tool cooling

Coolant inducers are used to retrofit through tool cooling to existing machine tools. A rotary coupling redirects the momentum of the LN_2 to have the same angular velocity as the spindle and channels it towards the centre of a hollow tool shank. The LN_2 is forced down and through a tool directly into the cutting zone. The concept layout of a cryogenic coolant inducer is shown below in Figure 6-7. Boring or drilling applications are possible due to the through tool coolant capability. For multiple tools, multiple inducers are required in the machine tool to allow for tool change.

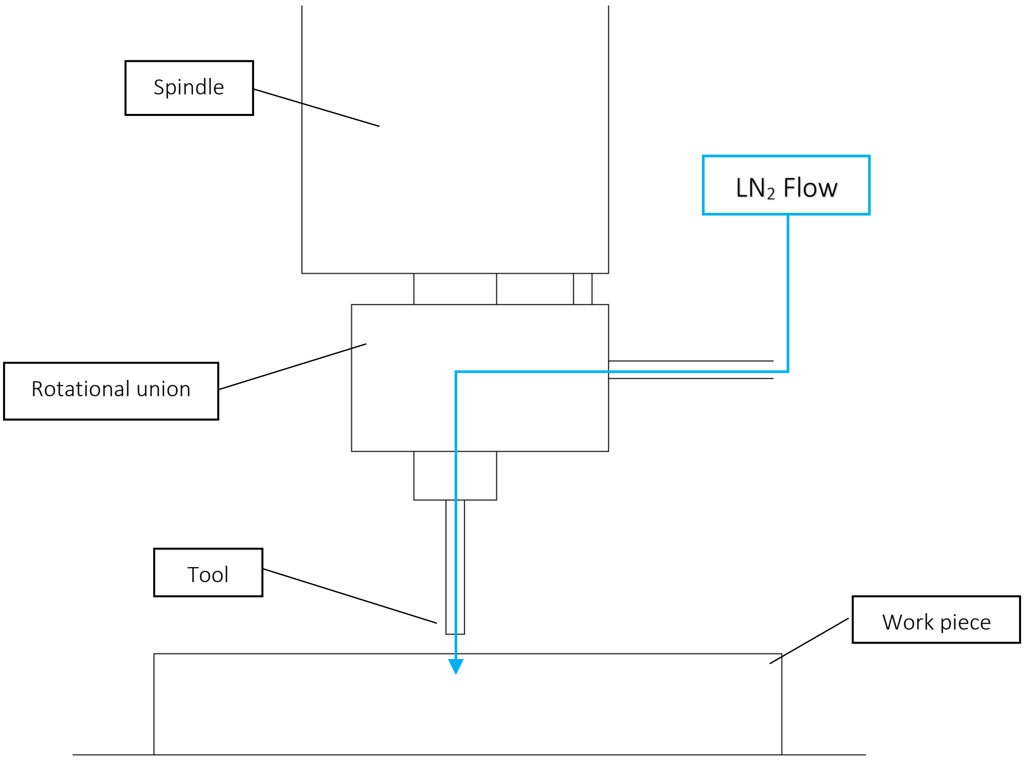


Figure 6-7 - Cryogenic coolant inducer concept

IV. Concept 4 – Cryogenic inducer with external tool cooling

This concept utilises a rotational union around a tool shank. The flow of LN_2 is directed around the tool shank and into several spray nozzles positioned around the body. Figure 6-8 shows a concept of the external body mounted to the shank on a bearing. The LN_2 spray nozzles can be specifically positioned towards the cutting zone. By tool changing between different inducers the nozzles can each be shaped to the specific tool and machining program. Each operation can have its own specific nozzle solution.

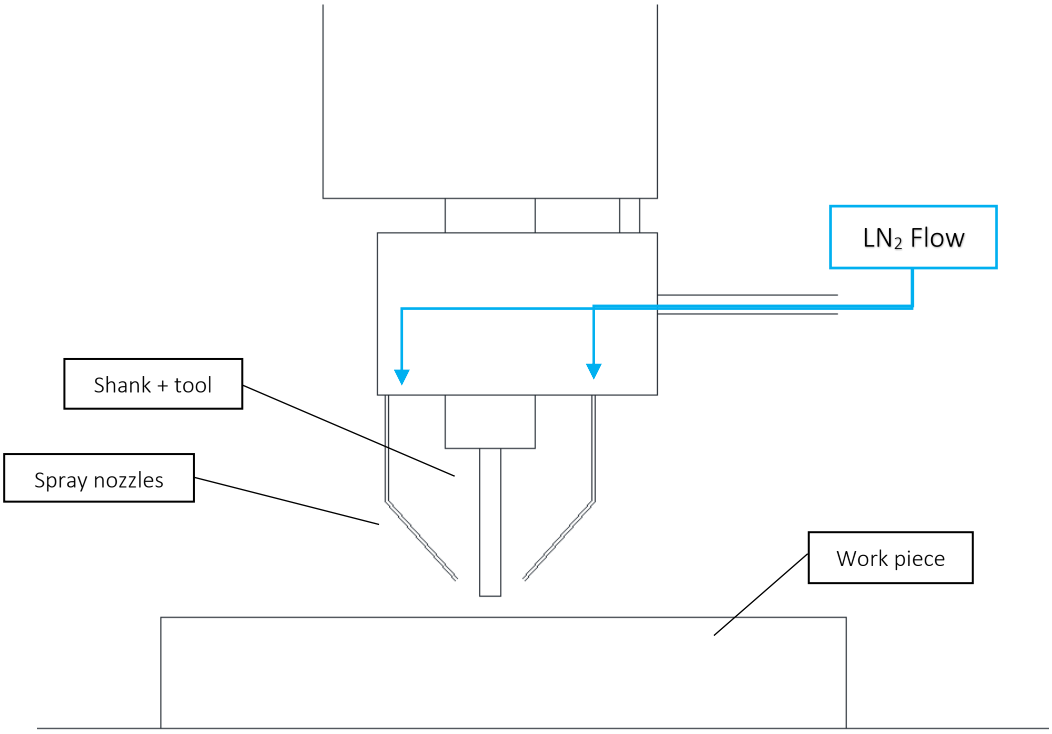


Figure 6-8 – LN_2 spray nozzles concept

6.4 Weighted selection between concepts

This section evaluates the concepts against criteria defined by the requirements in chapter 5.1. A Pugh concept selection matrix has been used and is shown in Table 6-2.

Concepts have been compared through weighted criteria in Table 6-2, compared to a baseline standard which was chosen to be the direct spray line. The coolant inducer concept has the highest total score suggesting that it is the best concept for further development. It must be recognised that qualitative and not just quantitative justifications must be offered.

Table 6-2 - Pugh concept selection matrix

	Pugh Concept Selection Matrix	Weighting	Direct Spray line	Pickup Rig	Coolant Inducer	Spray Nozzles
Mechanical Properties	Able to deliver a flow of LN_2 to the cutting zone. *The coolant inducer offers the greatest benefit – coolant is delivered through tool - therefore holes can be drilled etc.*	5	S	S	+	S
	Able to be retrofitted to many existing machining centres, both vertical and horizontal. *In this regard all are seen to have very similar requirements in terms of what modifications need to be done to the machine.*	5	S	S	S	S
	Able to withstand the fluid flow at -196^{0}c from LN_2. *This is a basic requirement that all must satisfy to operate.*	5	S	S	S	S
	Transmits sufficient force to machine difficult to machine materials. *Mandatory requirement.*	5	S	S	S	S
	Does not suffer any undue vibrational issues. *Mandatory requirement.*	5	S	+	+	S
	Must be able to work with existing tool suite. *Several inducers could be housed in a machine tool each with the required tool, these could be tool changed between. In solutions involving external nozzles the positions would need to be optimised for each tool.*	3	S	-	+	-
	Time between service intervals. *The spray line concepts would have very few or no moving parts leading to minimal wear, the inducer would require servicing intervals.*	3	S	+	S	+
	Ability to revert back to a flood coolant process if required. *The inducer does not require the removal of existing flood coolant nozzles which the other concepts may require due to space constraints. For switching a CNC program back to using standard coolant*	2	S	-	+	-
	There should be no leaks in the system. *The external concepts rely on well-established technology of insulated cryogenic pipes to bring the LN_2 to the cutting zone and have no moving fluid couplings.*	3	S	+	-	+
	System should be easy to control the flow rate and to switch on or off. *This will be controlled by a valve before the retrofit cryogenic machining system.*	3	S	S	S	S
	Can be easily taken in and out of a machine tool with minimal tools and no complex calibration/alignment. *The inducer can be removed like a normal tool mounted in a shank, or tool changed out.*	4	S	-	+	-
	System should be designed with easy disassembly in mind as well as assembly for problem finding and servicing.	3	S	S	+	+

Economical	Uses economical quantity of cryogen. *Achieving the requirement of providing LN_2 to the cutting zone will require a lesser flow rate from the inducer due to through tool cooling. External nozzles must spray more LN_2 to reach the cutting zone to overcome the amount that will be lost to boiling off in the atmosphere.*	5	S	-	+	-
	Cost to manufacturers. *All systems offer a lower price entry point than a standalone system to manufacturers. The pickup rig would potentially require medication to machining programs.*	5	S	-	+	+
Health & Safety	Should be easy to use and handle including loading/unloading from a machining centre. *Inducer could be removed like a tool shank. The advantage is that the inducer can be removed without touching any of the LN_2 supply pipework.*	4	S	-	+	S
	Complies with safe lifting regulations.	3	S	-	S	S
	Total +		*0*	*3*	*12*	*5*
	Total -		*0*	*9*	*1*	*6*
	Total Score		**0**	**12**	**13**	**10**
	Weighted Total +		*0*	*16*	*42*	*15*
	Weighted Total -		*0*	*-30*	*-6*	*-16*
	Weighted Score		**0**	**-14**	**36**	**-1**

6.5 Failure mode and effect analysis (FMEA) of selected concept

A failure mode effect analysis (FMEA) has been undertaken to highlight problems that may or are likely to arise during use. Failures with high risk priority numbers (RPN) represent critical failures that would invalidate the concept. Actions must be taken to lower the risk. From the FMEA several points of priority have been identified.

Table 6-3 – Concept FMEA

Design FMEA										
O -Probability of occurrence S - Severity of occurrence D - Probability of detection		1: Very rare → 10: Frequent 1: No Effect → 10: Most Severe 1: Certain to Detect → 10: Cannot Detect			RPN Values High H> 125, Medium 50<M<125, Low L<50					
Function	Failure Mode	Effects	S	Causes	O	Detection		RPN	RPL	Actions
						Current controls	D			
Piping cryogenic line into machine	Line becomes damaged. Line becomes trapped/pulled	Damage to equipment. Incorrect operation. Damage to equipment, Cryogen leak.	5	Machining failure, trapped during movement	2	Travel limits for axes programmed in to machine tool.	1	10	L	None XYZ travel limits set on machine. Only programs used that have been dry tested before. G code to be checked.
	Flexi pipe incorrectly attached	Damage/leakage	5	Incorrect fitment.		Manual testing before use.	1	5	L	
Rotational union	Friction from impact/incorrect assembly of design	Equipment damage, seizing of rotational union from friction or damage.	10	Soft limits with machining. Only known safe programs to be used.	5	Tested with assembly.	3	150	H	Inducer to be tested at both ambient temperature and cryogenic to ensure free movement.
	Damage to seals	Incorrect function of seals, leak, inefficient use of cryogen.	5	Incorrect assembly, friction damage.	5	Inducer rotated when assembled by hand to check for friction.	2	50	M	Inducer to be tested at ambient then cryogenic temperature.
	Thermal contraction	Leaks, damage, seizure of rotary coupling,	8	Incorrect design, material properties different to calculated, parts machined out of tolerance.	8	Hand testing.	2	128	H	Inducer to be tested at ambient then cryogenic temperature to check for ease of rotation. Regular stops during testing to ensure ease of rotation.
	Leaks from seals	Leaks – cryogen not forced into centre of union.	7	Damage to seals. Incorrect assembly. Incorrectly sized part.	7	All parts to be designed with suitable tolerances. Parts to be measured after production. Water testing after assembly.	4	196	H	Disassembly, precise measurement of parts to check + redesign.
Tooling	Tool damage/failure	Flow paths damaged/blocked	6	Tool at end of machining life, impact, incorrect machining parameters.	2	Visual inspection.	1	12	L	Only previously tested machining programs will be used. Tool inspected regularly.

The FMEA has identified certain factors that return high RPN values that must be reduced. All machining programs will be run without the machining workpiece in place to check for collisions.

Thermal contraction rates between ambient and cryogenic temperatures will be calculated for all components designed for the inducer. Materials will be selected that have low coefficients of thermal expansion. The inducer will be designed such that the function is not impeded when at room temperature and at cryogenic temperatures (77K). The design of the inducer must be able to rotate both at room temperature and the inducer will be assembled and rotated manually to check the fitment of parts at both room and cryogenic operating temperatures. Regular stops will be made and the inducer rotated by hand to check that seizing of the rotational parts does not occur.

6.6 Embodiment of design

The most suitable concept, coolant inducer, has been selected above by evaluating it against other generated ideas. A coolant inducer designed for flood coolant was acquired and reverse engineered as a test to determine the feasibility of the concept. In this section, the detailed design is explained to produce a first prototype. Detailed engineering drawings and a bill of materials are created.

Requirements for a cryogenic coolant inducer are summarised below:

- Machine volume limitations – the design must fit within the available tool and magazine volume of the machine.
- Material requirements – consideration must be taken to select the most suitable materials. This will be critical with environmental, mass, strength and thermal properties.
- Typical use – considerations such as tooling, tool change and how an operator would work with the inducer.
- Manufacture – the inducer must be designed for assembly and disassembly for servicing and testing.

Supporting methods to the design work are detailed below including calculations.

6.6.1 Example operation

The inducer must operate within a routine machining cycle for a typical 2.5D part. The area of investigation that this work covers is defined in the scope: automatic tool changing is a well-established technology in industry and will not be considered. It is added as a critical part of a normal coolant inducer operation for completeness. Tool changing allows for a tool suite using different inducers and will be essential to produce a product comparable to that which is accepted in industry.

Figure 6-9 shows a typical expected usage cycle for an LN_2 coolant inducer. When the specific tool is required the program will call up a tool change to that tool and load it into the spindle. As discussed in the literature section, a cool down cycle is required where LN_2 will be run through the inducer to reduce the surrounding temperature to enable liquid flow of LN_2 to the tool tip.

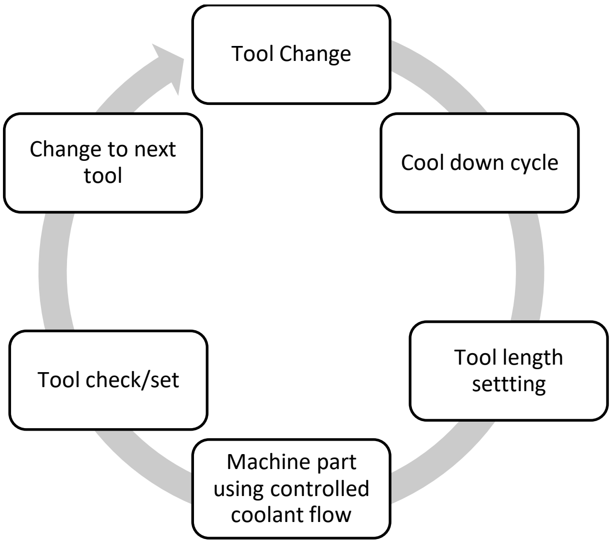


Figure 6-9 - Typical machine operation

A tool change will bring the next required tool into the machining volume.

6.6.2 Machining volume limitations

The chosen setup utilises a Bridgeport VMC 610 XP vertical machining centre, shown below in Figure 6-10.

Figure 6-10 – Bridgeport VMC 610 XP vertical machining centre

The volume requirements are such that the design must allow for complete free movement with no collisions during a machining cycle. The inducer must satisfy the volume limitation of the magazine/tool disk, transfer arm and the spindle. From the original specification drawings, attached in **Error! Reference source not found.**, a safe working volume of 350mm tool length and 200mm diameter has been decided. This was obtained from finding the lower volume limit from two areas of the machine that can be occupied by a tool.

6.7 Analysis of flood coolant inducer

Through disassembling a coolant inducer designed for flood coolant, a list of parts and their functions has been identified. The inducer has been reverse engineered to work with LN_2. This section provides a short summary of the initial testing of the first iteration of the cryogenic coolant inducer and discusses the validity of adapting existing designs used for retrofitting conventional flood coolant to machining centres. A flood coolant inducer was sourced and dismantled. The purpose was to establish if and how this unit could be modified to channel LN_2. Through the disassembly process, a series of parts were identified along with their functions.

I. Rotational union

This receives the flow of LN_2 from the spindle and channels it through a right-angled joint. The LN_2 enters an annular gallery around the inside of the union where it is forced into the rotating shank under the normal coolant pressure of the machine tool. This body contains parts for the tool change function which are outside the scope of research.

Figure 6-11 – Rotational Union (Body)

II. Bearings

The bearings are sealed units with steel races and balls. Polymer seal are used to prevent leakage of water based lubricant.

III. Tool shank

As shown in Figure 6-12 there are side entry holes recessed into a gallery on the outside diameter for through tool cooling.

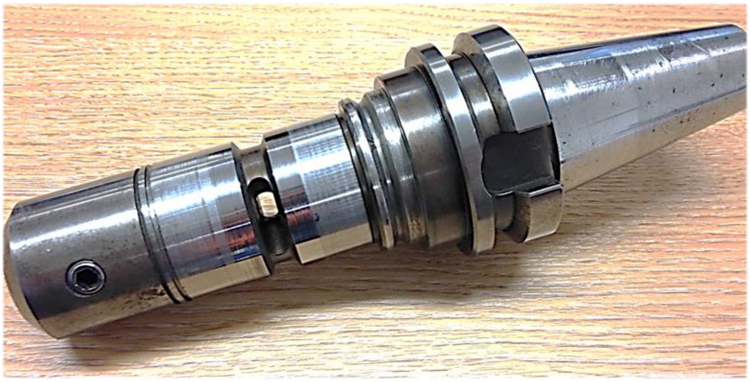


Figure 6-12 - Shank

The shank was hardness tested, producing a result of 50HRB on the Rockwell scale. The shank was measured on a CMM and modelled in CAD (by author), shown in Figure 6-13. This was necessary to design new components around the existing shank in CAD before creating engineering drawings and manufacturing parts. It was decided to maintain the use of the existing shank and adapt the body, bearings and seals for use with LN_2 as a first off feasibility test.

Figure 6-13 – Original shank CAD

Figure 6-14 shows a cross section from a typical flood coolant inducer. Coolant is piped into the machining volume from a line down the outside of the spindle where a connector is mounted. This allows the machining centre to tool change when the tool or coolant application is required.

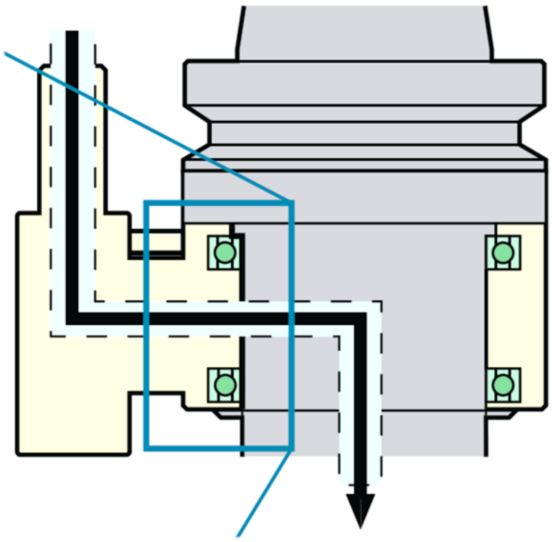


Figure 6-14 – Rotary union in flood coolant inducer (Precision and Systems, 2009)

Using this method, the coolant must be forced against the rotational forces of the tool shank. LN_2 boils at 77K. This leads to a volume expansion and a dual state flow with pockets of gas in the LN_2. Expanding gas leads to a violent explosive boil with gas escaping through the easiest route. This means that a cool down cycle will be required to allow all components.

The FMEA conducted in chapter 5.5 has identified high technological risks in the design of the rotary union and the sealing arrangement used in the transport of the LN_2. The di-atomic molecules have a very low affinity between each other. A boiling point of 77K means that any surface warmer than this will cause a state change to gaseous and a rapid pressure spike. This will present difficulties with any mating faces and seals to maintain pressure, as identified in the FMEA. The body taken from the acquired inducer is unsuitable for use with LN_2. Figure 6-15 below shows the redesigned body (by the author)) for use with the shank, manufactured from 303 stainless steel. The body was produced in Renishaw by the author using a CNC milling process.

Figure 6-15 – Manufactured replacement rotational union body

The body was designed by the author and was manufactured on a machining centre by Renishaw. Stainless steel 303 has been selected for its superior thermal contraction properties when compared to the original cast aluminium. The thermal contraction would compress the bearings increasing rotational friction. The current connection comprises of a hollow dowel pin that connects during a tool change. It is lightly sealed using rubber O-rings and is not fit for use with LN_2 as they would become brittle and disintegrate over a short period of time. In a machine tool, using a retrofit coolant inducer with standard coolant, damage to the bearings from low temperature is not acceptable. Below -85^{0}c standard oil and grease based lubrication is not feasible as the freezing mechanism will disrupt the movement of the ball bearings.

Ceramic materials have a lower expansion rate than metals (Marquardt, Le and Radebaugh, 2002) making them ideal for cryogenic applications. Ceramic ball bearings will contract significantly less than more standard steel versions and can still work at these extreme temperatures. In addition, ceramic bearings can withstand the thermal shock of being subjected to cryogenic temperatures.

Thermal contraction values have been determined by Reed & Clark (1983), a summary of common metals is shown in Figure 6-16 below. Thermal expansion is not greatly affected by material composition until large changes are introduced. This is important as thermal contraction values can be more accurately determined as the exact material composition of the original shank is unknown. Through analysis it has been determined to be a carbon steel alloy with a Rockwell hardness value, RC, of 54. It is therefore not unreasonable to use a CTE as an average of typical steels.

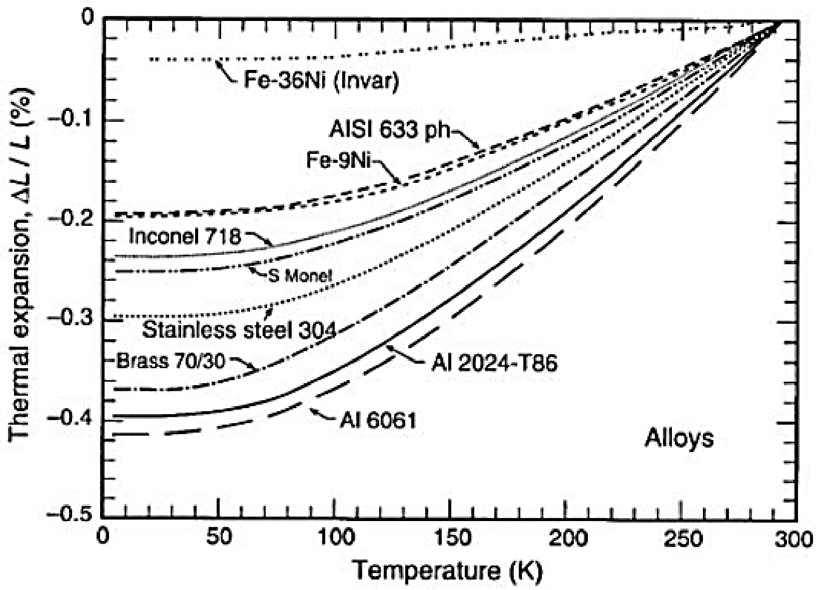


Figure 6-16 – Thermal contractions of metals at low temperatures

The change in circumference due to temperature change is expressed below in equation 1:

$$Ø_1 = Ø_0 \, (\Delta T\alpha + 1) \tag{1}$$

Where:

Φ_1 = Final diameter

Φ_0 = Initial diameter

ΔT = Temperature change

α = Coefficient of thermal expansion (CTE)

Table 6-4 summarises the results calculated for the original and newly manufactured components. The contraction values over the intended usage temperature range (77K - 300K) are displayed as percentage changes. The most important consideration is the diametric change of components as this will either result in a loose fit or friction from the contact between components. The original body was manufactured from cast aluminium. This has a greater percentage contraction than the stainless-steel replacement. More importantly, the diametrical change between the new body and existing shank is similar (10µm difference). The body will not contract to the same extent as the rotating shank. The seals form the critical rotational union between the body and shank. Polyether ether ketone (PEEK) has been selected for the seals material. The coefficient of thermal expansion (CTE) of PEEK is shown in Figure 6-18. Between 77K and 300K the diametric change equates to 1 mm when submerged in LN_2. PEEK benefits from not becoming brittle at cryogenic temperatures and has a low coefficient of friction (Theiler *et al.*, 2002). When assembled in the adapted body, there are flanges that rest on flat sections inside the body. As the seal contracts, it will remain in contact with the body due to being fastened from above and below by a retaining ring. Figure 6-17 shows the seals (redesigned by the author) which are ridged on the inside face. These ridges are designed to aid sealing by allowing the nitrogen gas to expand into them before escaping through the next narrow section. This design of seal also has the advantage that each ridge can wear individually, thus forming a more custom fit that helps to maintain the pressure between on the LN_2.

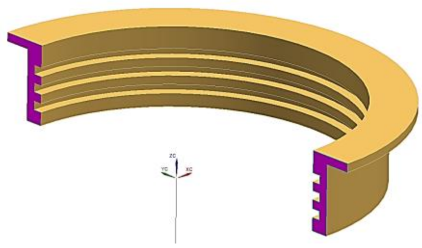


Figure 6-17 – PEEK seals with inner ridges

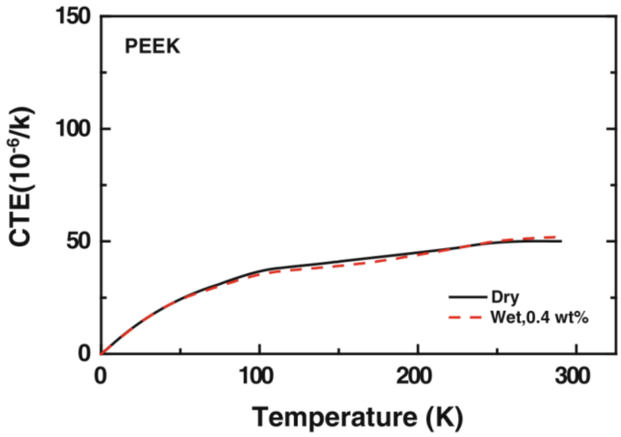


Figure 6-18 – Thermal expansion of PEEK (Kalia and Fu, 2013)

Table 6-4 – Calculated thermal contraction values

Part	Material	Δø (77-300K) *(%)*	$ø_0$ (mm)	$ø_1$ (mm)	Δø (mm)	Δ Radial (mm)
Shank	Hardened Steel	-0.30	40.00	39.88	0.12	0.06
Body (existing)	Aluminium	-0.40	45.00	44.82	0.18	0.09
Steel body	303 stainless	-0.30	45.00	44.87	0.13	0.07
Brass seals	Brass	-0.45	50.00	49.81	0.19	0.09
PEEK seals	PEEK	-2.00	50.00	49.00	1.00	0.50

Figure 6-19 shows an exploded assembly of the reverse engineered inducer. Parts have been redesigned around the existing tool shank to create a rotational union. The body receives the LN_2 line and forces it in between new PEEK seals into the shank body where it is directed downwards. A 12mm end mill has been sourced with through tool coolant which enters and leaves the tool through 3 separate coolant channels. Importantly this cutter is a standard off the shelf unit – a potential key requirement for end users. Parts are listed in Table 5-5.

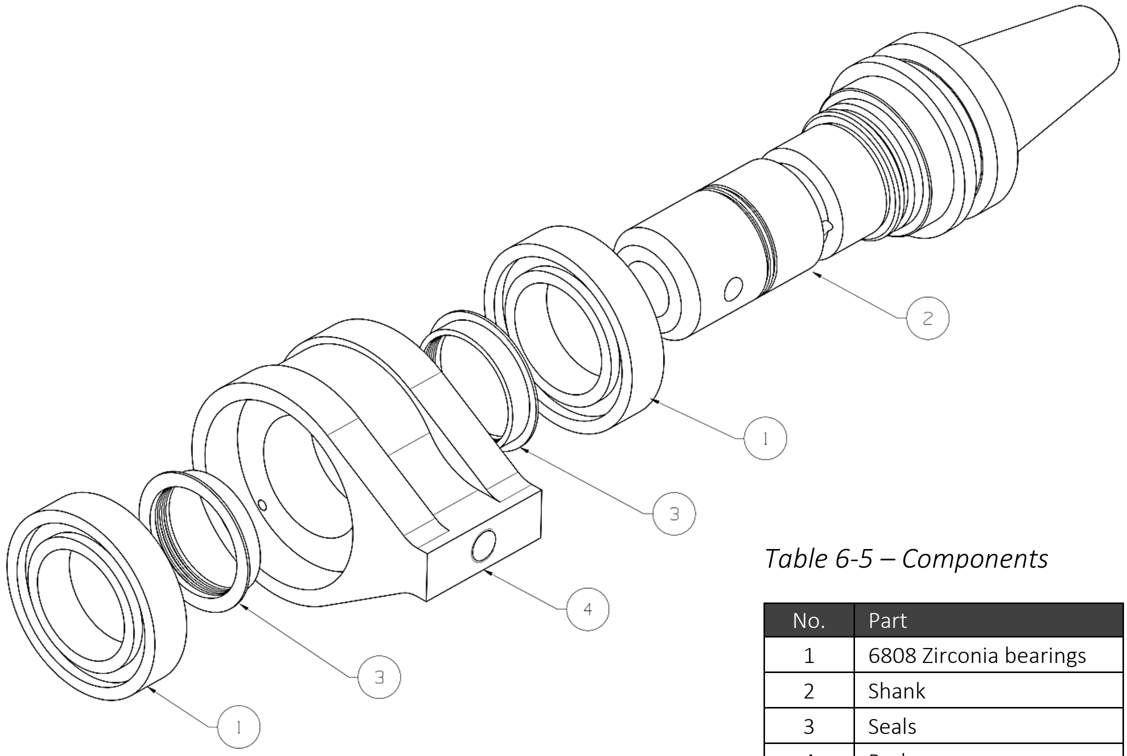
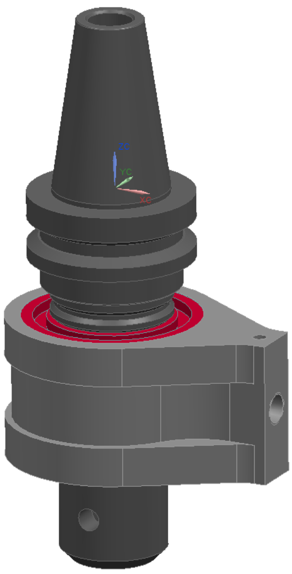


Table 6-5 – Components

No.	Part
1	6808 Zirconia bearings
2	Shank
3	Seals
4	Body

Figure 6-19 – Exploded view of adapted coolant inducer



a.

b.

Figure 6-20 – CAD (a.) and built (b.) of reverse engineered inducer

The inducer was designed for simple assembly and disassembly. Press fitting was chosen with all components being held together by a threaded retaining ring. The seals were pressed in followed by the shank. The whole assembly was secured with a retaining circlip to the end of the shank.

6.8 Testing of adapted coolant inducer

The inducer was set up for testing on a Bridgeport VMC610 XP machining centre. Spindle rotation was started at 200rpm followed by gradual increases up to 2000rpm without using any coolant. There was no resonance and the shank span freely within the housing; the bearings ran and sounded smooth. It was noticed that the inducer had warmed after the rotation. The cryogen was fed through the inducer and liquid nitrogen exited the holes of the cutting tool. Upon inspection, it was observed that due to the extremely low temperatures, water vapour from the air had condensed and frozen onto the surface of the inducer. Due to the formation of ice on the moving surfaces the rotation was no longer smooth and provided a large resistive torque. The inducer was left to warm up to the ambient temperature before rotation testing with the cryogen, starting at 100rpm increasing gradually up to 1000rpm. Figure 6-21 shows the inducer rotating whilst LN_2 is running through it. As the gassing off time was passed, liquid flow was observed. The spindle load began to increase, shown on the machine tool's controller. The test was stopped due to the spindle automatically cutting out due to a large detected force. For safety reasons, the test was halted.

Figure 6-21 – Testing reverse engineered flood coolant inducer with cryogen

When the inducer was at 300K (the approximate ambient temperature) the shank rotated freely within the bearings. Only when LN_2 was introduced to the system, the rotational torque began to increase. The inducer was dissembled for inspection. Both seals had suffered frictional rotation damage, shown Figure 6-22. The PEEK seals were subject to a greater contraction than originally calculated. This caused the inner diameter to contact the shank and the outer diameter to shrink away from the body, evidenced in Figure 6-22 which shows the frictional wear has occurred on the outer ring. The seals rotated with the shank, causing the wear. The contraction direction is shown in Figure 6-23.

Figure 6-22 – PEEK seal showing friction/heat damage

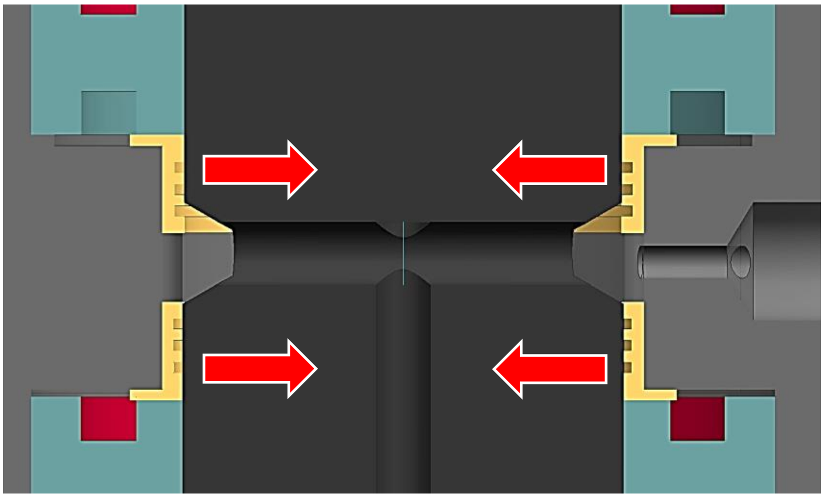


Figure 6-23 – Image showing seal contraction

To summarise, reverse engineering the flood coolant inducer has yielded a flow of LN_2 to the tool tip. This initial test has shown that using a coolant inducer concept is feasible for delivering a flow of LN_2 to the cutting zone and is worth developing further. The test also highlighted several issues. The seals caused friction between body and shank. A different sealing method will be designed and implemented. The lower bearing was open to potential contamination. A lower guard will be designed to be protected from flying debris from machining. A collet system will be introduced that allows for ease of change of the cutting tool. It is estimated that the inducer must be rotating when LN_2 is introduced to the system to prevent pre-run ice build-up from water vapour on bearings.

7 Cryogenic inducer concept design

All of the design work detailed in this chapter is the work of the author unless otherwise stated.

In this chapter, a cryogenic inducer is designed and manufactured using the methodology outlined in chapter 4. A test plan in is written in chapter 7.1 is written to assess the performance of the design against the PDS detailed in chapter 6.1.

The function of the coolant inducer is to direct LN_2 to the tool and work piece interface. The design concept is shown in Figure 7-1. A vacuum insulated line of LN_2 is brought into the machining volume of the machine tool. It is connected to a rotational union which directs the flow into a tool shank and to the tip of the tool. The body remains stationary whilst the shank rotates. Bearings are required as well as seals to prevent leaks.

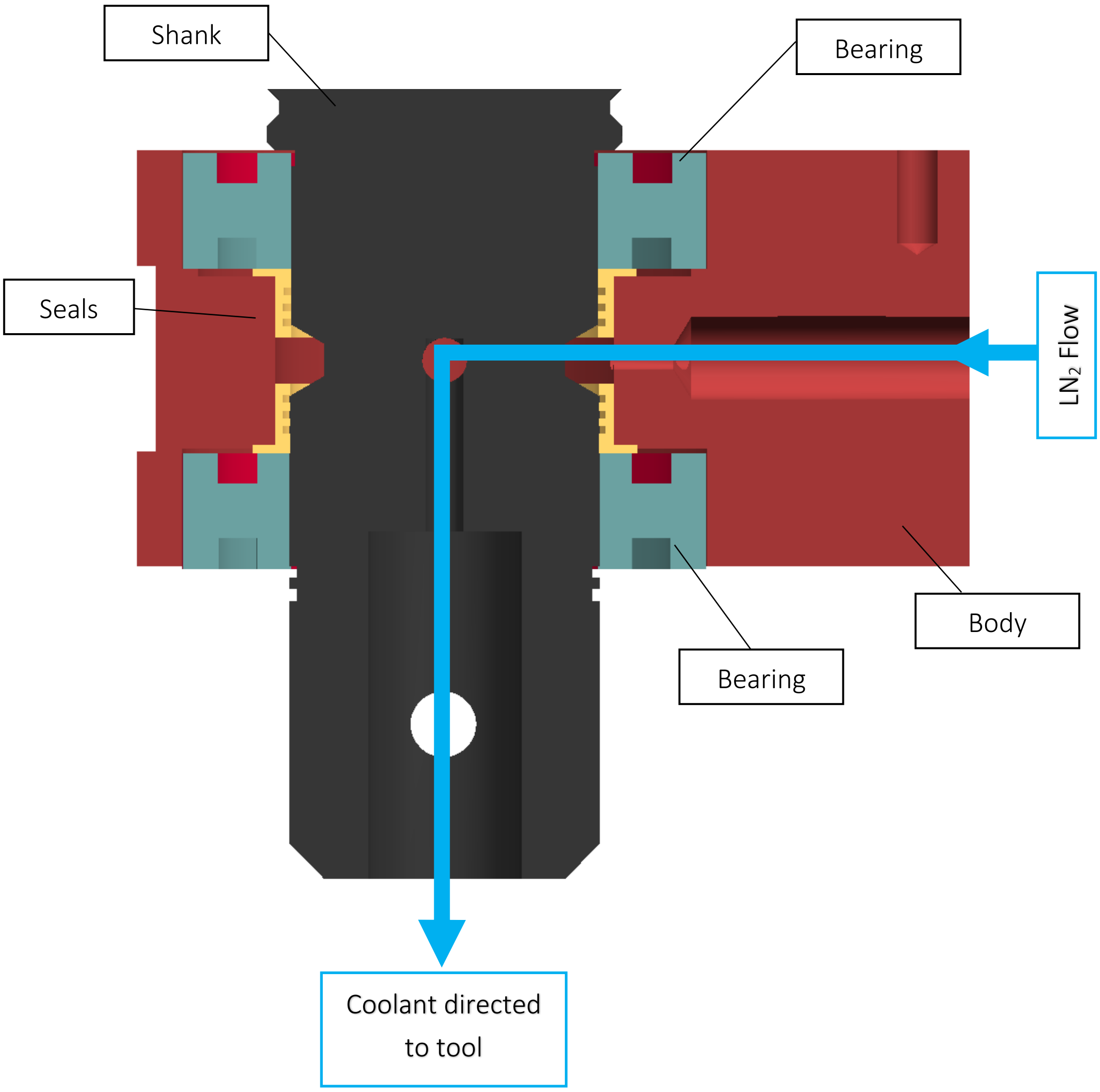


Figure 7-1 - Cryogenic inducer concept

Based upon the methodology detailed in chapter 5, the black box functions for each physical component were developed as shown in Table 7-1. These functions are ranked based on their priority. Sealing the flow of cryogen through the rotary union was identified as critical to the function of the inducer, therefore the sealing arrangement must be considered first.

Table 7-1 – Part function breakdown

Part	'Black box' functions	Non-functional implementation req.	Non-functional performance req.
Body	Receives LN_2, forces into rotating shank. Holds assembly together.	Connector interface to LN_2 line – BSP pipe connection.	Survives temperature. Fitment not affected by temperature operating range.
Shank	Directs LN_2 in to tool. Holds tool to along cutting path.	BT40 standard. Holds mill cutter.	Fitment not affected by temperature operating range.
Seals	Maintain pressure across rotational union.	Prevent leak. Rotate freely.	Fitment not affected by temperature operating range. Low friction to allow free rotation of the shank
Bearings	Facilitate rotation of shank.	Operate at low temperatures.	Fitment not affected by temperature operating range.
Tool	Cuts metal	Through tool coolant holes.	Selected 'bought' part suitable.
LN_2 line	Deliver LN_2 flow in to machine volume.		Standard pipe connections.

The interface between the rotating shank and the supply of LN_2 has been identified in the FMEA in 0 as having the highest risk of not performing the required function. The component design process will begin with the seals and shank.

7.1 Test procedure

To assess the performance of the cryogenic inducer, it will be tested and evaluated against the requirements. The function of the inducer is to provide a flow of LN_2 to the cutting zone at suitable cutting speeds, therefore the ultimate test will be machining material with LN_2 flowing through the inducer. Before this is attempted the device must be tested for safety and correct operation. There is a requirement for it to be able to rotate both at room temperature and with LN_2 flowing. This is to ensure no damage to the device during normal operation: the device should be able to be rotated without coolant, or if the coolant were to cut out during use.

Table 7-2 below details the procedure for assessing the performance of the new design. This is a stepped list developed by the author based on current machining practice in industry, the inducer must meet or exceed the criteria set out in each point sequentially.

If failing at each point for any reason, the test will not be allowed to continue. For example, the inducer will at first be rotated by the machine spindle at a reduced rate and stopped. It will then be removed from the machine for visual inspection. This is both for safety and to prevent damage to equipment. The inducer will be scrutinised for general usability such as replacing tools, loading and unloading into a spindle and to check that the shank is rotating freely. The test plan will be performed using no LN_2. It will then be repeated using a flow of LN_2 to the inducer.

Table 7-2 - Cryogenic coolant inducer test procedure

No.	Test	Success Criteria	Procedure
1	Inducer leak test using water line whilst not rotating.	Water leaves inducer through tool tip. No leak paths observed. Inducer still rotates freely when pressurised.	Observation for leaks. Disassembly + dry components.
2	General usability	Tool easy to fit/remove. Can be loaded in to machine in as with a normal tool. Can be lifted with one arm up to a machine spindle.	Issues that impede use.
3	Dry rotation at 250 rpm	Inducer rotates easily – no excess friction/heat generated	Disconnection and hand testing. Machine controller monitored for sudden spikes in force.
4	Dry rotation increasing speeds up to 3000 rpm	No excess friction or noise generation whilst running dry for several minutes at a time.	Machine controller monitored. Disconnection and hand inspection after each high rpm run.
5	Introduction of LN_2 to system – non-rotating.	Flow of LN_2 to the tool tip.	Visual inspection. Feeling for pressure under tool tip with gloves.
6	Rotation at 250 rpm with LN_2.	Flow of LN_2 from tool tip. Inducer does not seize.	Machine controller monitored. Disconnection and hand inspection after each high rpm run.
7	Rotation increasing speeds up to 3000 rpm with LN_2.	Flow of LN_2 from tool tip. Inducer does not seize. No excessive noise/vibration.	Machine controller monitored. Disconnection and hand inspection after each high rpm run. Visual observations.
8	Use in machining program	Does not suffer damage when being used to cut material.	Inspection after use for wear. Quantification of any wear through disassembly.

7.2 Detailed design and specification of components

In this section, components are designed following the design methodology outlined in chapter 4. The tooling and bearings are selected as detailed in the methodology and illustrated in Figure 5-2.

I. Shank

The shank must meet the following requirements:

- Able to be manufactured for different machine fitting standards (BT40, HSK63 etc.)
- Must be able to withstand cryogenic temperatures (77K).
- Must withstand cutting forces from machining operations.

Typical cutting forces required for milling typical Ti-6Al-4V are presented by Ezugwu & Wang (1997). The shank will be subject to a feed force consisting of an x and y components, shown by F*x* and F*y*. The resultant force vector is shown as F*f* in

Figure 7-2. The shank will also be subject to a rotational torque and a vertical reaction force, or downwards pull from the workpiece.

Figure 7-2 shows the forces from a planar perspective, as a 2-dimensional problem.

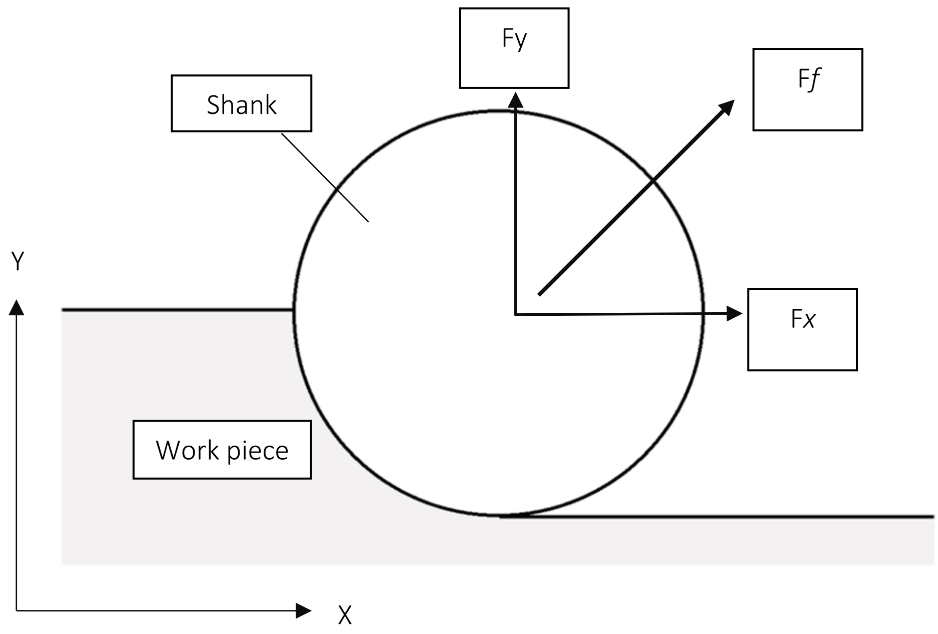


Figure 7-2 - Forces on shank (plane view)

Alauddin *et al.*, (1998) conducted research into machining Inconel 718. It was found that the feed force increased with both depth of cut and feed rate. The maximum force produced was under 600N, for a 2.4mm depth of cut and a feed rate of 70mm/min.

Commercially available coolant inducers are available with a large variety of standard tool shank options to suit different machining centres. For this research BT40 shank was selected as this is the standard compatible with the Bridgeport VMC 610 XP. As there is a requirement to modify the shank to fit all of the coolant inducer's components, a blank shank was selected as shown in Figure 7-3. This will allow a custom shank to be manufactured that is compatible with the developed design. If the inducer design fits within the allowed volume, it is possible to source different versions of the same inducer, e.g.; BT30, HSK, CAPTO. This would allow for adoption of through tool cryogenic machining for various existing machining centres.

Figure 7-3 – Blank BT40 shank (Wohlhaupter, 2017)

These blanks can be bought in varying diameters and shank standards. The design of the inducer can be adapted simply by changing the tool blank allowing for different standards.

Detailed drawings for the shank design can be found in the Appendix III. The shank is designed to be machined from a tool blank and finished for the specified tolerances. This allows for close tolerances with the rotating components e.g. bearings and seals. The ER collet has been adopted for the design. Developed in the 1970's by Rego-Fix, it is widely used in machine tools. The collets have a wide clamping range for tool shank diameters between 0.5mm to 35mm (Rego-Fix, 2017). An ER collet will allow for ease of change of the cutting tool and will be suitable for through-tool coolant capabilities.

II. Rotational seals

During the testing of the reverse engineered flood coolant inducer, gaseous leaks were visible between the shank and body. The sealing arrangement retrofitted to the existing inducer was not satisfactory. The LN_2 must be forced towards the centre of a rotating mass. The sealing arrangement must be such so that the path of least resistance for the LN_2 is from the body in to the shank and out of the tool to the cutting interface.

For the materials selection process CES selector 2017 was used (Granta Design Limited, 2017). The material selection requirements for a rotational labyrinth seal composed of two rings. Each are summarised as:

1. Able to withstand cryogenic temperatures (77K).
2. The material must retain toughness at 77K and be subjected to plastic not brittle failure.
3. Able to withstand vibrations, impacts and the forces of a typical machining cycle.
4. Must have low friction properties to allow for any friction caused by misalignment.
5. The material selected should have a relatively (compared to similar choices) low thermal contraction percentage when cooled from ambient temperature down to cryogenic temperatures (77K).

With exacting assembly, labyrinth seals are non-contact. A metal on metal contact during rotation is likely to lead to friction weld rendering the inducer useless and unable to be disassembled. It is therefore essential that the outer and inner labyrinth rings are both a polymer and two dissimilar materials with good friction characteristics between each other. They rely upon the intermeshing fins and it is acceptable for parts to wear into each other to compensate for any misalignment from assembly. CES selector has identified multiple materials that meet the requirements and are detailed in Table 7-3.

Table 7-3 - CES selector results (Granta Design Limited, 2017)

Material	Comments
Fluorinated ethylene propylene (FEP)	Good impact strength and thermal contraction properties. High cost per billet of material.
PAI (Polyamide-imide) Several brand names such as Torlon, Duratron	Very stable with excellent friction properties. Sourcing correct billet size has been found to be problematic with high costs and long lead times.
Perfluoroalkoxy alkane (PFA)	Good thermal properties and strength. High cost. Billet size required (OD 80mm) proving hard to source and high cost.

Table 6-3 (continued) - CES selector results (Granta Design Limited, 2017)

Material	Comments
Polyamide-imide (PI)	Price per unit strength better with PI.
Polytetrafluoroethylene (PTFE)	Excellent dry lubrication properties. Relatively low cost compared to other alternatives.

PTFE was selected for the seal material. At ambient temperatures, the predominant wear of PTFE is self-adhesion. Shearing occurs from two surfaces binding. The friction coefficient of PTFE decreases as the temperature is reduced to 77K. At this point the predominant wear mechanism is abrasion (Theiler *et al.*, 2002). PTFE displays approximately 15% elongation to failure. It deforms without shattering at 77K. It presents a low coefficient of friction between contact to itself (PTFE on PTFE) and to metals such as aluminium and steel (Theiler *et al.*, 2002). An analysis of the effects and design considerations of operating between ambient and cryogenic conditions is presented in chapter 7.3. Labyrinth seals are non-contact. The outer and inner faces rotate with a gap of the order of 0.1mm between each rotating fin making the seal frictionless. Two potential labyrinth sealing solutions were identified: horizontal and vertical. A horizontal arrangement is shown in Figure 7-4 whereby the outer ring is split in two to allow for ease of assembly. The outer ring must be split to fit around the outside during assembly.

The seals were designed and manufactured by the author using a CNC Mazak mill-turning machine. PTFE presented a problem whereby the required tolerances were not being achieved, both diametrically and in height of the fins. It is believed that due to its relative flexibility (in comparison to steels for instance) caused the PTFE to elastically deform away from the turning insert. The heat generated from the machining process will also have caused the material to expand, leading to an incorrect depth of cut. These are both examples of the difficulties in the machining of polymers that were discussed in 3.1. In the manufacturing of each seal the dimensions were checked on a CMM. If the parts were not within specification (as per the drawings detailed in appendix III) further work was done on a manual lathe to remove minimal material before re-measuring. It must be stated that this process was followed to produce the required small number of development parts. Were the parts to be produced in large numbers a custom cutting tool would be produced that would produce the correct shape of fins in a fraction of the cycle time, thus actually making large volume production easier.

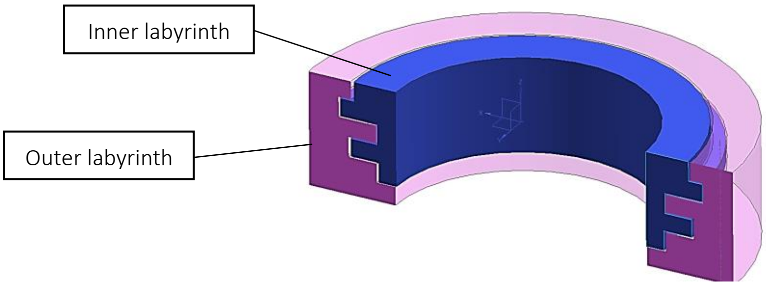


Figure 7-4 – Horizontal finned labyrinth seal

III. Cutting tools

The inducer is designed to accept readily available ('off the shelf') tooling by using the ER collet design. This makes the inducer flexible for different tool requirements. Specific tooling designed for cryogenic machining is not required to be developed.

A Mitsubishi carbide end-mill was selected for testing with the inducer, shown in Figure 7-5. The tool has coolant channels built in that deliver coolant to the tip of the tool. As the tool rotates the holes deliver coolant at the bottom of cutting face.

Figure 7-5 – Mitsubishi end mill (Mitsubishi Advanced Materials & Tools Company, 2016)

Through using equation 2, spindle speeds can be calculated based upon tool diameter and the cutting speed.

$$Spindle\ Speed\ (rpm) = (v_c \times 1000)/(\pi \times D_{cap}) \qquad (2)$$

Where:

v_c = Cutting speed (m/min)

D_{cap} = Cutting diameter (12mm)

For use with 12mm diameter end mill cutters, a spindle speed between 1000-2500 rpm is typical with a surface speed of 50-80 metres per minute recommended by the manufacturer (Mitsubishi Advanced Materials & Tools Company, 2016). For a range of cutters between 6mm and 16mm shank diameter, the spindle speed would vary between 900 – 5000 rpm.

Therefore, the inducer must be capable of providing a flow of LN_2 to the cutting zone between these rotational speeds.

IV. Rotational union (body)

The rotational union (body) serves as the outer housing to the tool shank. It has the function to 'Receive LN_2 from static line and direct the LN_2 into the rotating shank'.

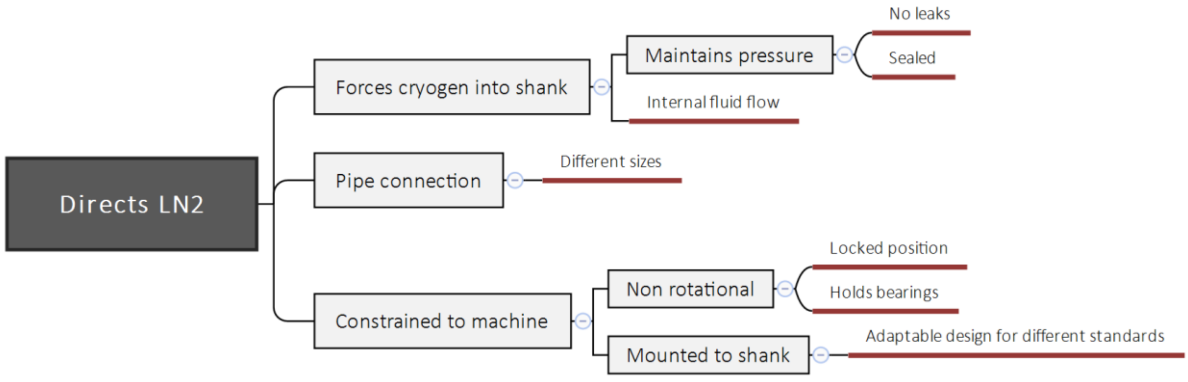


Figure 7-6 - Function break down

Additively manufactured (3D printed) body has been designed to house the seals and bearings on the shank.

An isometric CAD view is shown in Figure 7-7(a) of the body. By using additive manufacturing, it is possible to create an annular gallery within the body. The purpose is to allow LN_2 to flow around the outside, reducing the differences in the vector components of the rotating shank. This will increase the contact time with the shank holes. The internal gallery allows LN_2 to feed into the rotating shank from the body (a) shown in in Figure 7-7(b). Holes around the inside of the gallery face inwards towards the shank.

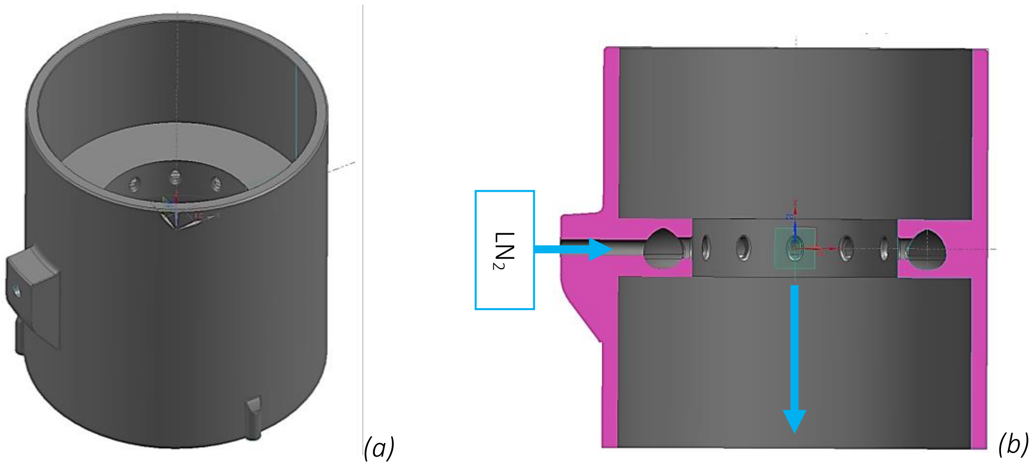


Figure 7-7 – (a) CAD Isometric view, (b) Section view

Titanium Ti–6Al–4V has been selected for the material. It exhibits a -0.1% linear thermal contraction coefficient between ambient and cryogenic temperatures (Reed and Clark, 1983). Through cooling from ambient temperature (293K) to the liquid point of Nitrogen (77K), the contraction has been calculated. An analysis of the effects and design considerations of operating between ambient and cryogenic conditions is presented in section 7.3.

The force acting upon the outer race of the bearings will be decreased due to the decreased thermal contraction. The first adapted inducer did not contract enough to lock the bearings in place. An increase in torque was detected by the machine controller acting upon the spindle. This was partly due to the water vapour condensing in to ice around the bearings. It may also have been partly due to the thermal contraction of the body.

Another benefit of using additively manufactured titanium body was mass reduction. The Titanium version has a mass of 320g in comparison to the 740g of the stainless steel body which was manufactured for the adapted flood coolant inducer. This mass saving will beneift manual loading and unloading in to the machine spindle.

7.3 Tolerances and design for thermal constraints

Analysis of the adapted flood coolant inducer in chapter 6.8 and the FMEA in 0 have highlighted thermal contraction of different materials as being a critical issue. The parts forming the inducer must remain together during the cooldown and warmup cycle during intended use.

Assembly takes place at ambient temperature. The parts must not require excessive force for assembly or loosen when subjected to cryogenic temperatures. Material selection and part tolerances are critical.

The FMEA in chapter 0 identified leaks between the seals and shanks of having high RPN values. The potential causes were thermal contraction of components, out of tolerance parts and damaged seals. The body will contract on to the bearings. The inner labyrinth seals will contract onto the shank. The outer seals will contract potentially becoming loose from the body. The outer races of the bearings will be compressed potentially causing bearings to seize.

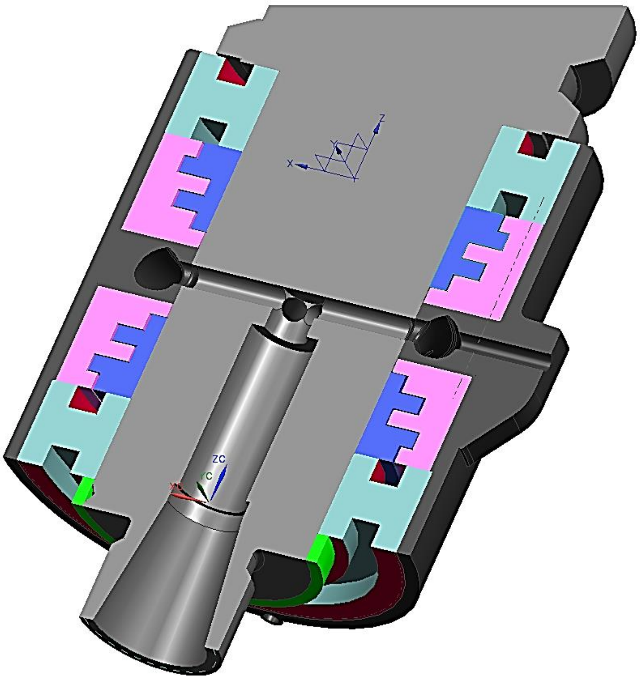


Figure 7-8 – CAD cutaway with horizontal labyrinth seals

As the inducer cools down during the use of LN_2, all components will contract with the temperature change. Labyrinth seals offer the advantage that the sealing action between the labyrinth fins will not be affected by this dimensional change being non-contact. Figure 7-9 shows the fitment of the seals inside the body. The inner labyrinth seals are designed to have an interference fit with the shank. The outer seals have an interference fit with the body. In between the inner and outer seals there is a frictionless air gap.

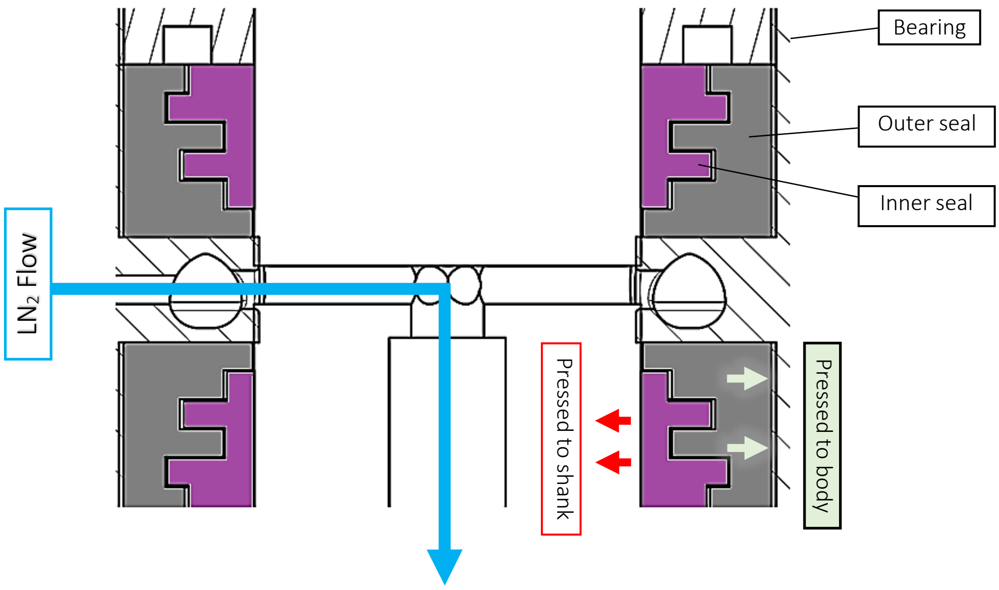


Figure 7-9 – Cross section of horizontal seals

Data has been taken from Reed & Clark (1983). All parts have been measured on a CMM to establish if they are in or out of tolerance, where appropriate, parts have been resized to fit during assembly. Thermal contraction calculations are presented in Table 7-4 below.

Table 7-4 - Thermal contraction of parts in LN_2

	Material	*α (%)*	$ø_0$ (mm)	$ø_1$ (mm)	Δ ø (mm)	Δ Radius (mm)
Shank	Hardened Steel	-0.30	40.00	39.88	0.12	0.06
Body	Ti–6Al–4V	-0.15	50.00	49.93	0.08	0.04
Labyrinth seals	PTFE	-2.00	50.00	49.00	1.00	0.50

The data presented in Table 7-4 has been calculated to inform upon the design of the inducer. The diametrical shrinkage between room temperature and 77K is presented.

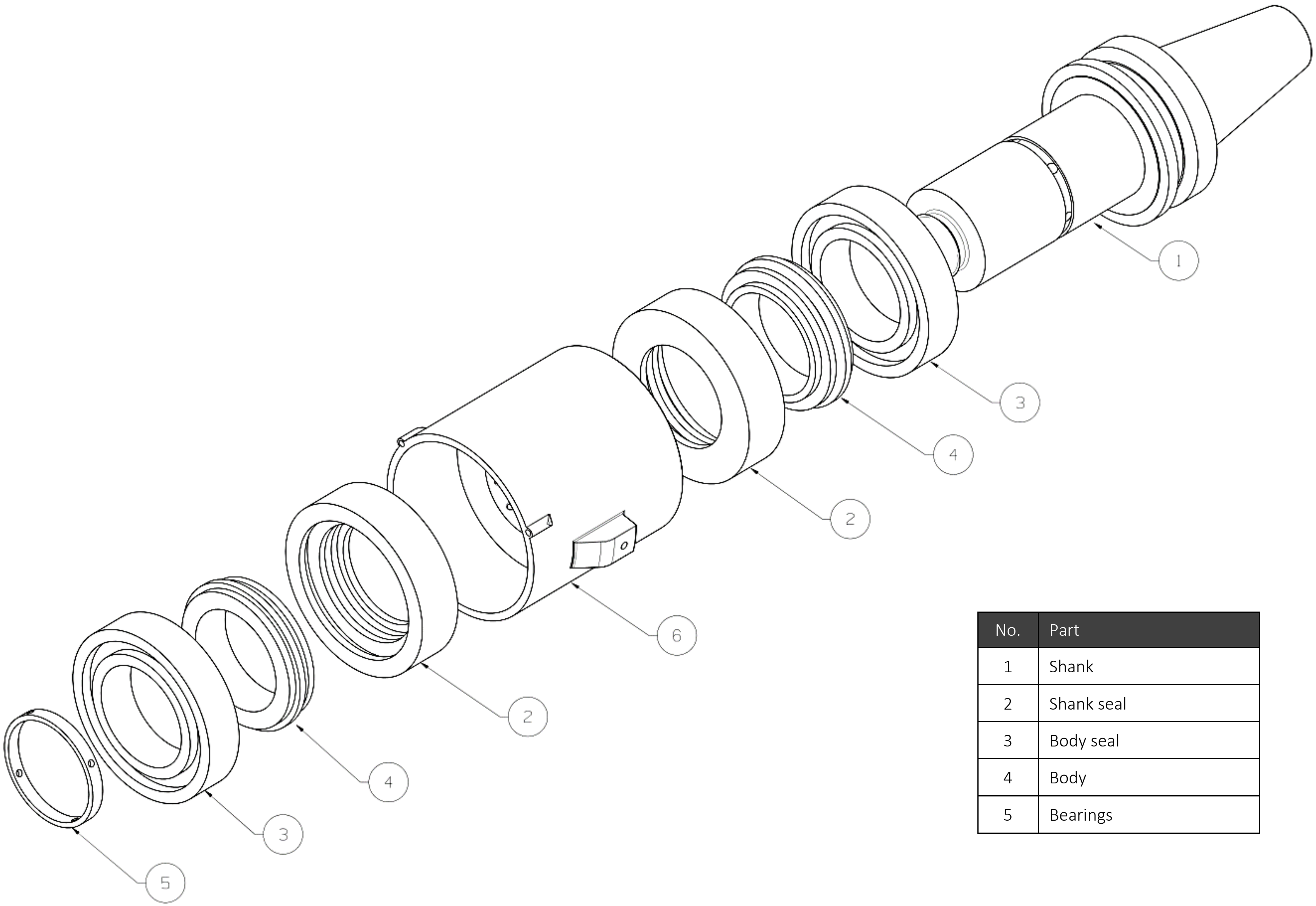
The shank will remain in contact with the PTFE labyrinth seals due to their increased shrinkage rate. The shank seal shrinks at a greater rate than the shank, therefore tightens onto shank when cooled. This will maintain the interference fit between the shank and inner seal. The body seal will be subject to shrinkage away from the wall of the body-potentially causing leaks. To maintain between the body and outer seal it will be bonded in place using sealant. The inner labyrinth will shrink on to the shank, thus tightening and staying in place with the rotation.

Through the calculations in in Table 7-4 each component has been designed to work both at room temperature and at 77K.

Engineering drawings for all components can be found in Appendix III. A tool blank was machined using a CNC lathe to the required geometry specified in the engineering drawings.

Figure 7-10 below shows the assembled first iteration. The lower bearing protective plate has been removed to show the placement of the bearing. The bearings were not exposed during testing. The parts were press fit together using a hydraulic press at ambient temperature. The force required to press parts together was monitored using the attached pressure gauge to check for any sudden spikes. The assembled inducer was connected to a water line to check for any leaks that may have been caused from an incorrect assembly. Results are detailed in chapter 6.4.

Figure 7-10 Assembled inducer with pipe attached for leak test



No.	Part
1	Shank
2	Shank seal
3	Body seal
4	Body
5	Bearings

Figure 7-11 – Exploded view of cryogenic inducer

7.4 Iteration 1 - Testing

This section details the findings from testing the inducer in the Bridgeport VMC610 XP milling centre. The test procedure detailed in Table 7-2 was followed.

The inducer was connected to a water line and checked for any leaks. The inducer was then dissembled to check and dry the components.

The general usability test showed that the design of the inducer made the general operation and changing cutters with the ER collet simple. The decreased mass compared to the first adapted feasibility trial made loading and unloading into the machine spindle possible with one arm.

The vacuum insulated LN_2 line was attached to the inducer. The spindle was test rotated in dry mode without LN_2. The rotational speed was gradually increased in increments, holding for 10 seconds at each one to observe the inducer. The test was halted at regular intervals to check for heat from friction. The inducer was removed from the spindle and rotated manually to ensure that it was running smoothly. The inducer was left running dry for 2 minutes at 3000rpm. It was then immediately removed from the spindle and checked. The inducer remained cool to the touch and there were no observed problems up to 3000rpm.

In chapter 6.8 the adapted coolant inducer was tested. It was discovered that water condensed out of the air on to the bearings causing them to begin seizing. To avoid this, LN_2 was introduced to the inducer spinning at 100rpm. Figure 7-12 shows the initial gassing off phase of the LN_2. Vapour was clearly observed to be passing out at high velocity from the tool tip.

At 200rpm, LN_2 was observed to be flowing from the tool tip. There were visible leaks through the races of the upper and lower bearings. At 300rpm it is estimated that half of the flow of LN_2 escaped through the leaks. As the spindle speed increased, these leaks gradually became greater. At 600 rpm, only a negligible amount of LN_2 was observed flowing from the cutter. Table 7-5 summarises the major observations taken during the testing.

Table 7-5 - Observations from testing of iteration 1

Spindle speed (rpm)	Observations
100	Good LN_2 flow from tool tip. Vapour leaks starting to occur from above and below inducer.
200	LN_2 flow from tool tip. Vapour leaks starting to occur from above and below inducer.
300	LN_2 flow reduced to around half of strength at 100 rpm. Leaks from top and bottom causing vapour plumes in machine.
400	LN_2 flow reduced. Leaks more violent.
500	No LN_2 to be observed leaving tool tip.

The inducer was disassembled to check all components individually. The labyrinth seals are showing signs of frictional wear. The two halves of the outer seal became loose from the inner face of the body and could be moved by hand. The seals were then removed from the body for further inspection. The PTFE inner labyrinth rotates freely within the outer seal. Some PTFE wear residue was observed within the intermeshing fins, showing that frictional wear occurred during the testing.

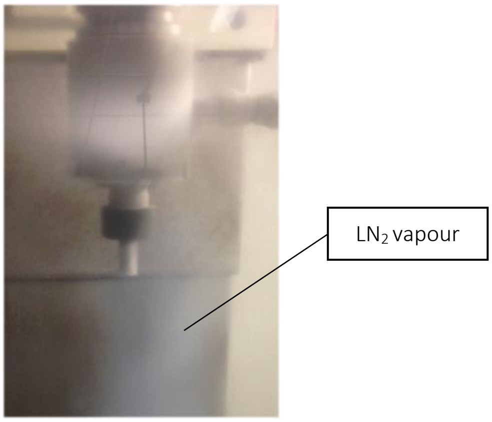


Figure 7-12 – Cryogen gassing off phase

After the test was completed, the inducer was removed from the machine and inspected. The tool coolant holes were clear and unobstructed from ice particles shown in Figure 7-13.

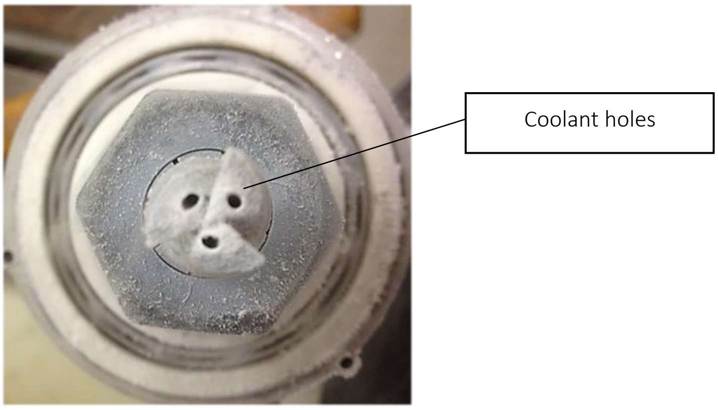


Figure 7-13 – Coolant holes after testing with cryogen

7.4.1 Iteration 1 - Technical review

Iteration 1 was manufactured and tested. The test plan detailed in Table 7-2 was used to test the cryogenic inducer in a machine tool environment by first rotating the inducer with no coolant or LN_2 and then by introducing a flow of LN_2. Nitrogen vapour was observed leaking from the upper and lower bearings. As the spindle speed increased, the leaks became greater. The testing was conducted up to a spindle rotation of 600 rpm where the LN_2 flow from the tool tip became negligible. At this point the testing was stopped. The FMEA in chapter 0 identified leaks between the seals and shanks of having high RPN values. The potential causes were thermal contraction of components, parts out of tolerance and damage to the seals.

The labyrinth seals used in the first iteration had horizontal fins. To assemble them, the outer seal had to be cut in half. This led to high material wastage due to twice as many having to be produced, one half being discarded to compensate for the diameter lost to the cut. Figure 7-14 shows the labyrinth seals in the body after testing. The join line between the outer halves can clearly be seen. Assembling the horizontal labyrinth seal highlighted that these could not be validated as being assembled correctly, or to what state the fins were in from the press fitting. The leak path could have been in between the shank and inner seal or through the join lines of the outer. The developed seals have failed to maintain enough pressure required to direct LN_2 in to the rotating tool at representative machining speeds (1000-5000 rpm).

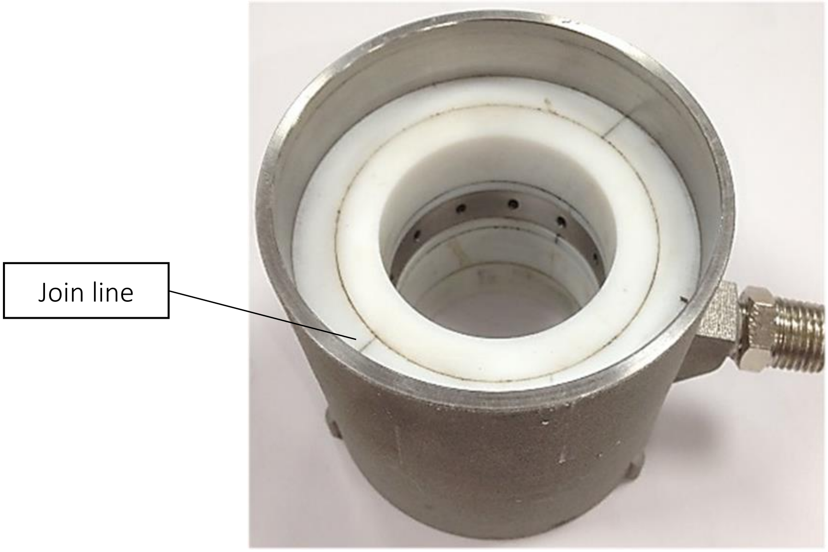


Figure 7-14 – Inside view of body after testing

The LN_2 was introduced to the system under a rotational speed of 100rpm. The machine controller was monitored for any increase in power that would indicate seizing but none was observed. The bearings were removed for visual inspection. No damage was observed and they still rotated freely and smoothly. These bearings can be re-used for future testing.

The shank was removed from the inducer for inspection and no damage was observed. The cutter could still be easily removed and replaced using the ER collet system. The additively manufactured Ti–6Al–4V body displayed no damage and was deemed suitable for reuse.

The test procedure has identified that the first iteration of the inducer has been able to deliver a flow of LN_2 to the tool tip.

The cause of the leaks has been identified as unsatisfactory sealing leading to leaking through both upper and lower bearings. The horizontal labyrinth design of the seals will not be tested further.

The initial water pressure test revealed no obvious leaks. The seals prevented leaking water at 2bar pressure whilst the inducer was not rotating. This test did not indicate potential leak when using LN_2 whilst rotating the shaft and therefore will not be carried out for future iterations.

Based on the findings of this experiment, another iteration was decided to be tested making use of an alternate seal design.

7.5 Iteration 2 – Detailed embodiment of concept

The cause of the leaks observed in the testing of the first iteration of the inducer has been attributed to the design of the horizontally finned labyrinth seals. An alternative, within the space constraints available, is to integrate the labyrinth fins vertically, as shown in Figure 7-15. Vertical fins lead to a simplified assembly process. Both the inner and outer seals can be fitted together as built.

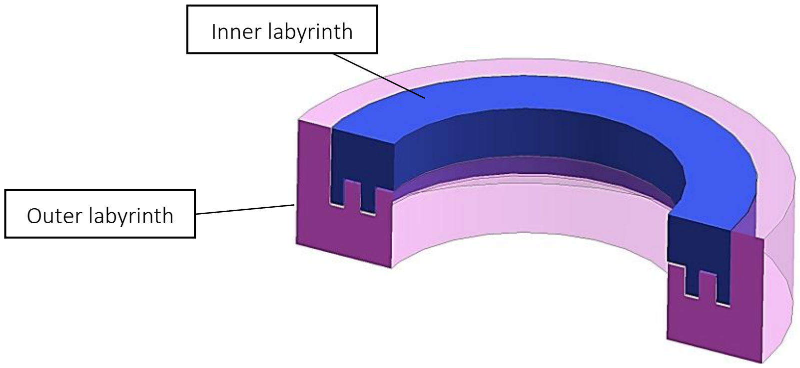


Figure 7-15 – Labyrinth seal with vertical fins

The new seals have been designed to fit within the available space in the same body, as demonstrated in Figure 7-16. Compared to the horizontal layout, they provide a decreased fin length but have the advantage of being manufactured ready to fit with no joining lines between the outer seals.

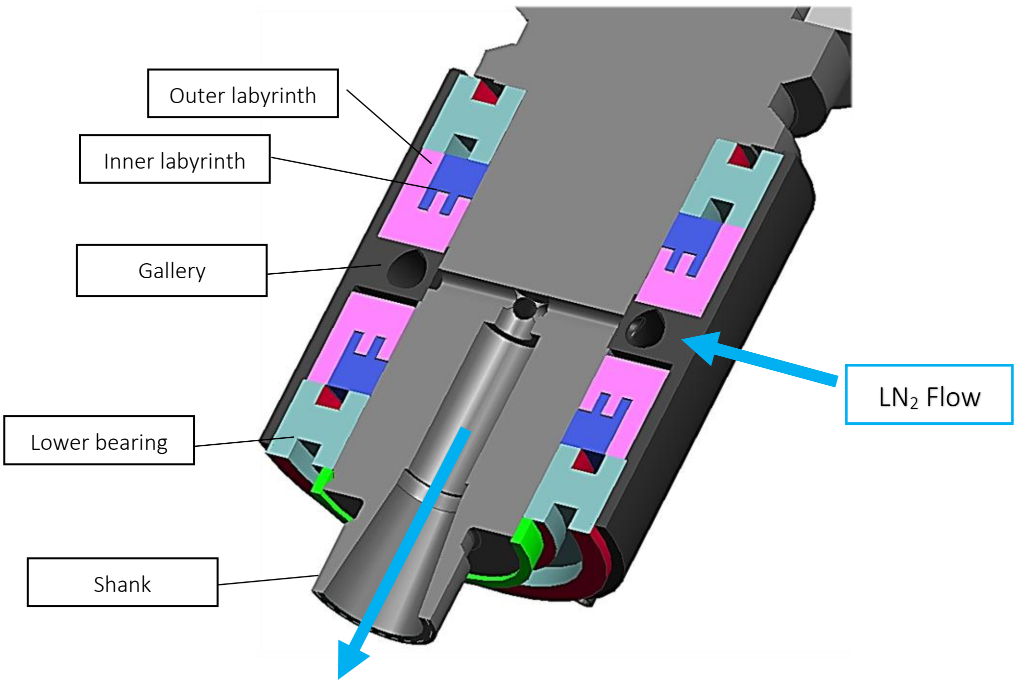


Figure 7-16 – Iteration 2 cutaway showing vertical labyrinth seal design

7.5.1 Iteration 2 - Lab testing

The seals were manufactured and assembled with the components used for iteration 1. The test procedure detailed in Table 7-2 was repeated. The dry rotation test showed the inducer to be rotating smoothly when being held manually. LN_2 was introduced to the system with the inducer at a spindle speed of 200 rpm. LN_2 was observed exiting the tool tip. Figure 7-17 shows LN_2 flow from the inducer during testing. The spindle speed was incrementally increased. At 300 rpm, nitrogen vapour was observed exiting from the upper and lower parts of the inducer. As the spindle speed increased, the leaks became stronger and the flow of LN_2 from the cutter decreased. At 700 rpm the flow from the tool tip reduced to zero with the majority of LN_2 escaping through the leak paths – that is through the upper and lower bearings. It was not possible to determine if the leak paths were from gaps between the bearings and shank, or between the races. Table 7-6 summarises the major observations taken during the testing of iteration 2.

Table 7-6 - Observations from testing of iteration 2

Spindle speed (rpm)	Observations
200	Good LN_2 flow from tool tip.
300	Good LN_2 flow from tool tip. Leaks starting.
400	Vapour leaks starting to occur from above and below inducer. LN_2 flow reduced slightly.
500	LN_2 flow reduced to around half of strength at 250 rpm. Leaks from top and bottom causing vapour plumes in machine.
600	Leaks increased further. Very little LN_2 to be observed leaving tool tip.
700	No LN_2 flow to be observed leaving the tool tip. All LN_2 to be observed being ejected from inducer between shank and body.
800	Unchanged.

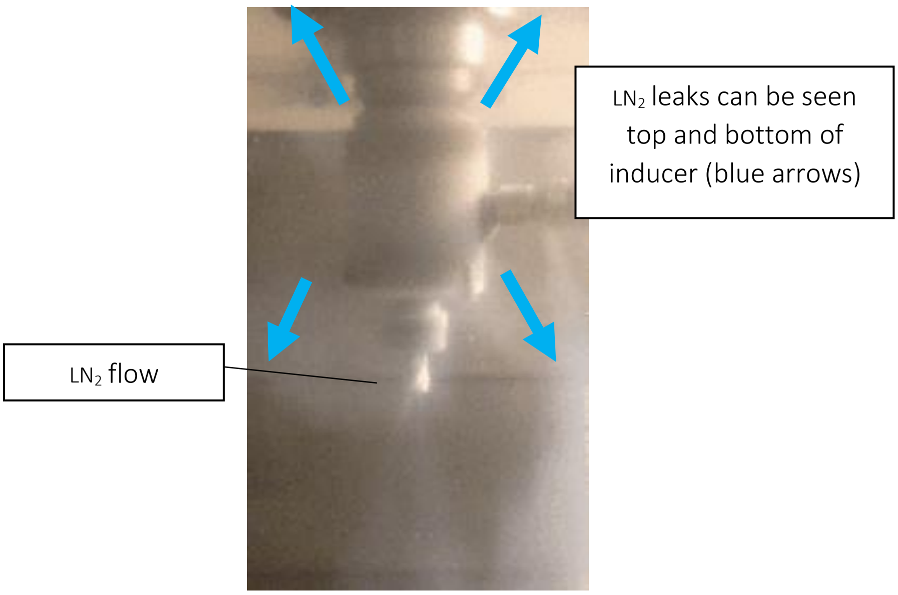


Figure 7-17 – LN_2 flow from iteration 2

7.5.2 Iteration 2 – Technical review

Iteration 2 was manufactured and tested. Labyrinth seals with a vertical fin arrangement were used. LN_2 flow was observed at spindle speeds up to 400 rpm. At greater rotational speeds than this, vapour began to escape from the upper and lower parts of the inducer. As the spindle speed increased further, the leaks became greater and the LN_2 flow from the tool tip decreased. When compared to iteration 1, the inducer could be run at an increased rotational speed for an equivalent flow of LN_2 from the tool. The point at which the flow became insignificant was 700 rpm versus 500 rpm. The labyrinth seals with a vertical fin arrangement have provided a greater sealing pressure – evidenced by the decreased leakage rate.

The test procedure identified that the second iteration of the inducer has been able to deliver an increased flow of LN_2 to the tool tip. The desired spindle speed for machining with a 12mm diameter tool was not satisfied.

The LN_2 is forced inwards against the centripetal outwards force from the rotation shank. As the rotational speed increased, this became noticeably worse. LN_2 escaped from between the shank and body. The labyrinth seals were not maintaining a large enough pressure to ensure LN_2 is directed in to the rotating shank.

As shown in Figure 7-8, the side entry coolant holes of the shank are orthogonal to the LN_2 flow direction within the body. The flow of LN_2 will undergo a pulsing back pressure due to the holes into the centre of the shank passing in between holes in the body gallery and wall sections. This pulsing leads to back pressure and will excite (heat) the LN_2. The flow is being disrupted by the sudden velocity change and the pressure or sealing arrangement is not enough to overcome this.

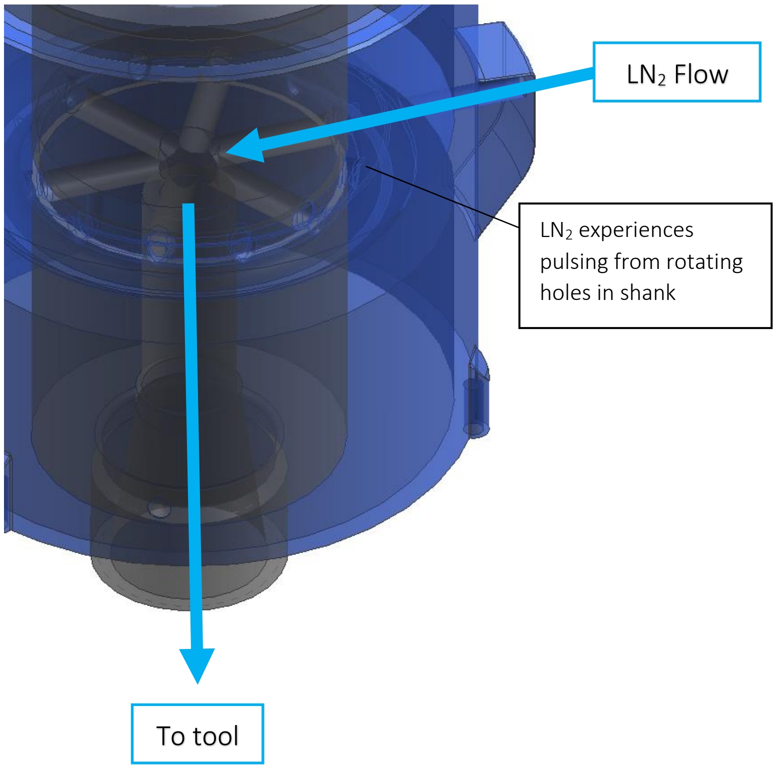


Figure 7-18 – LN_2 flow from body to shank

Based on the improvements seen with the alteration of the design of the labyrinth seals, a further design iteration was decided upon to attempt to solve the velocity component differences between the LN_2 and the rotating tool shank.

7.6 Iteration 3 – Detailed embodiment of concept

The leaks observed in the first two iterations increased with spindle speed. The flow of LN_2 from the tool tip reduces with the increase in spindle speed until becoming negligible. By altering the fin arrangement of the labyrinth seals from horizontal to vertical, this cut off point was increased to 700 rpm.

I. Axial impeller

To minimise the energy absorbed by the LN_2, an impeller has been designed (by the author). It has the function to redirect the LN_2 velocity vectors. The vanes act to force cryogen downwards and inwards – straight into the shank entry holes through a gradual curve as shown in Figure 7-19. The impeller presented in this work functions to move the LN_2 towards the centre of a rotating mass.

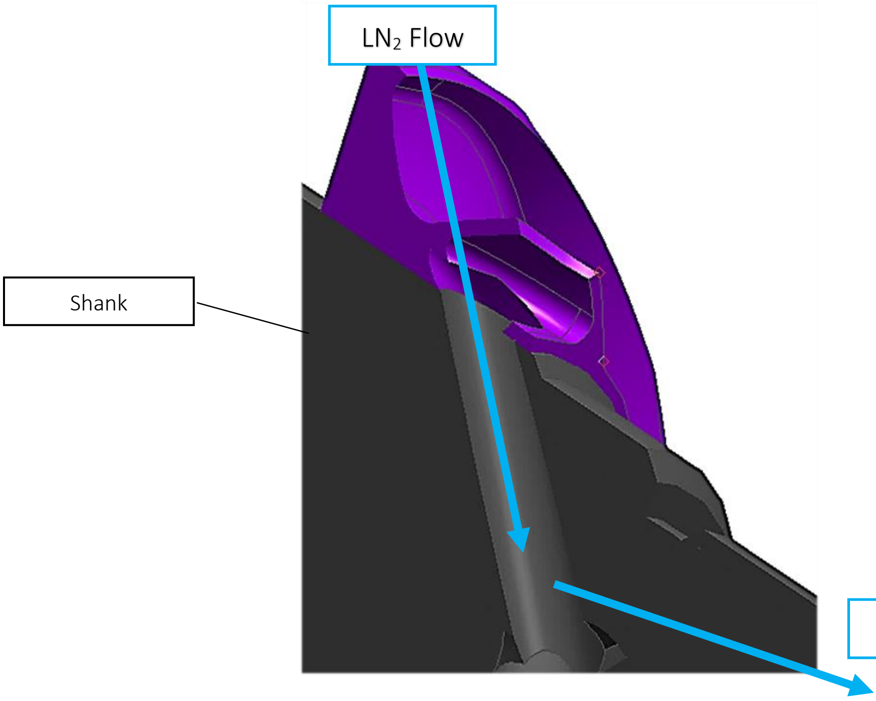


Figure 7-19 – Turbine/shaft interface

The form of the impellor vanes was derived through designing for the space constraints. Figure 7-20 below shows the physical space constraints that the impellor must fit within.

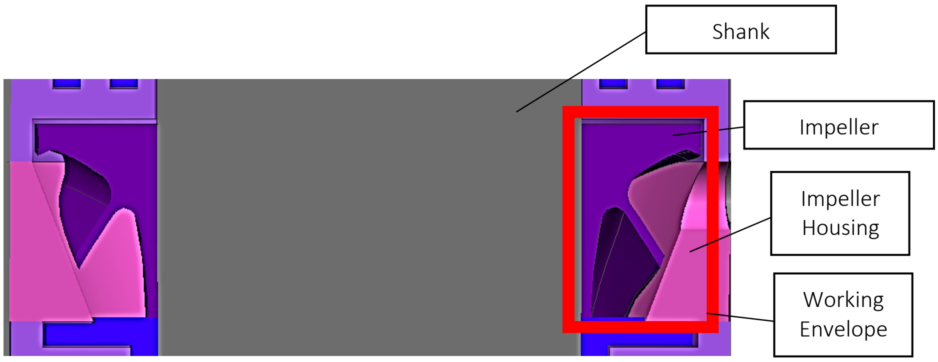


Figure 7-20 – Detail view of impeller space constraints

The red box shows the available space between the seals. A toroidal volume is created between the seals and the body. The form of the vanes has been created in 2D planes before combining to create a 3D extrusion. Within the red box above the vane must direct the flow through 90 degrees downwards, within the working envelope (approximately 20mm downwards and 15mm inwards towards the shank).

These will align with reciprocating holes in the shank, shown below in Figure 7-21 *(a)* and *(b)*. The LN_2 enters the body from a vacuum insulated line orthogonally to the shank. As it contacts a rotating fin, the liquid is forced into the shank and down to the cutting tool.

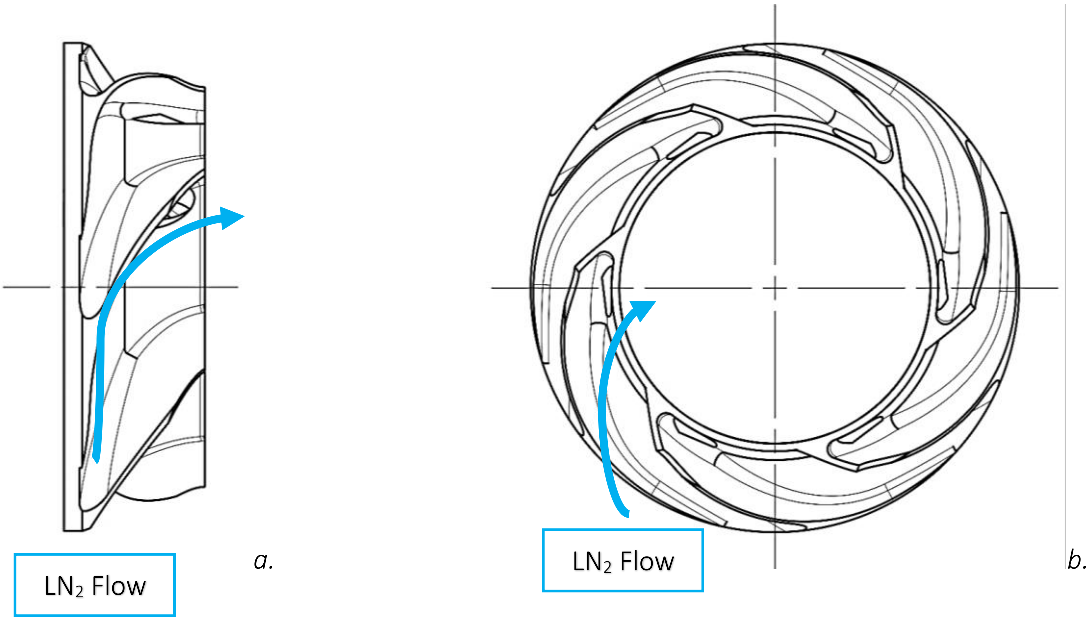


Figure 7-21 – Design of axial impeller a.) side view b.) plan view

The form of the impeller vanes have been designed to force the LN_2 along the face and into the shank. Figure 7-22 below shows the impeller additively manufactured manufactured from Ti–6Al–4V in a Renishaw AM250 3d printer. The surface has been silica grit blasted to achieve a smoother surface finish than the 'as printed' part. This component could also be manufactured completely, or finished from a near net shape such as a casting . As this is just a prototype additively producing complex geometry is made possible with the use of an additive manufacturing process (3d printing).

Figure 7-22 – Ti–6Al–4V additively manufactured turbine

II. Seals

Testing previous iterations of the inducer has demonstrated that labyrinth seals enabled a flow of LN_2 from the tool tip. At higher spindle speeds, the flow of LN_2 was blocked resulting in leakage around the seals. Seals using a vertical fin arrangement maintained a higher-pressure gradient. A greater spindle speed was reached before the flow reduced to zero from the tool tip.

The vertically finned labyrinth seals have been further developed to accommodate the impeller. They comprise of two pairs, one for each bearing end. A cross section is shown in *Figure 7-23*. Each pair of seals has been designed so that one half fits to the shank with an interference fit and the other to the body. The fitments are highlighted by arrows. By ensuring an interference fit, the leak path for the LN_2 will be between the labyrinth fins. The impeller rotates with the shanks. It is surrounded by a housing that wraps around it and is shaped to match the rotating vane forms.

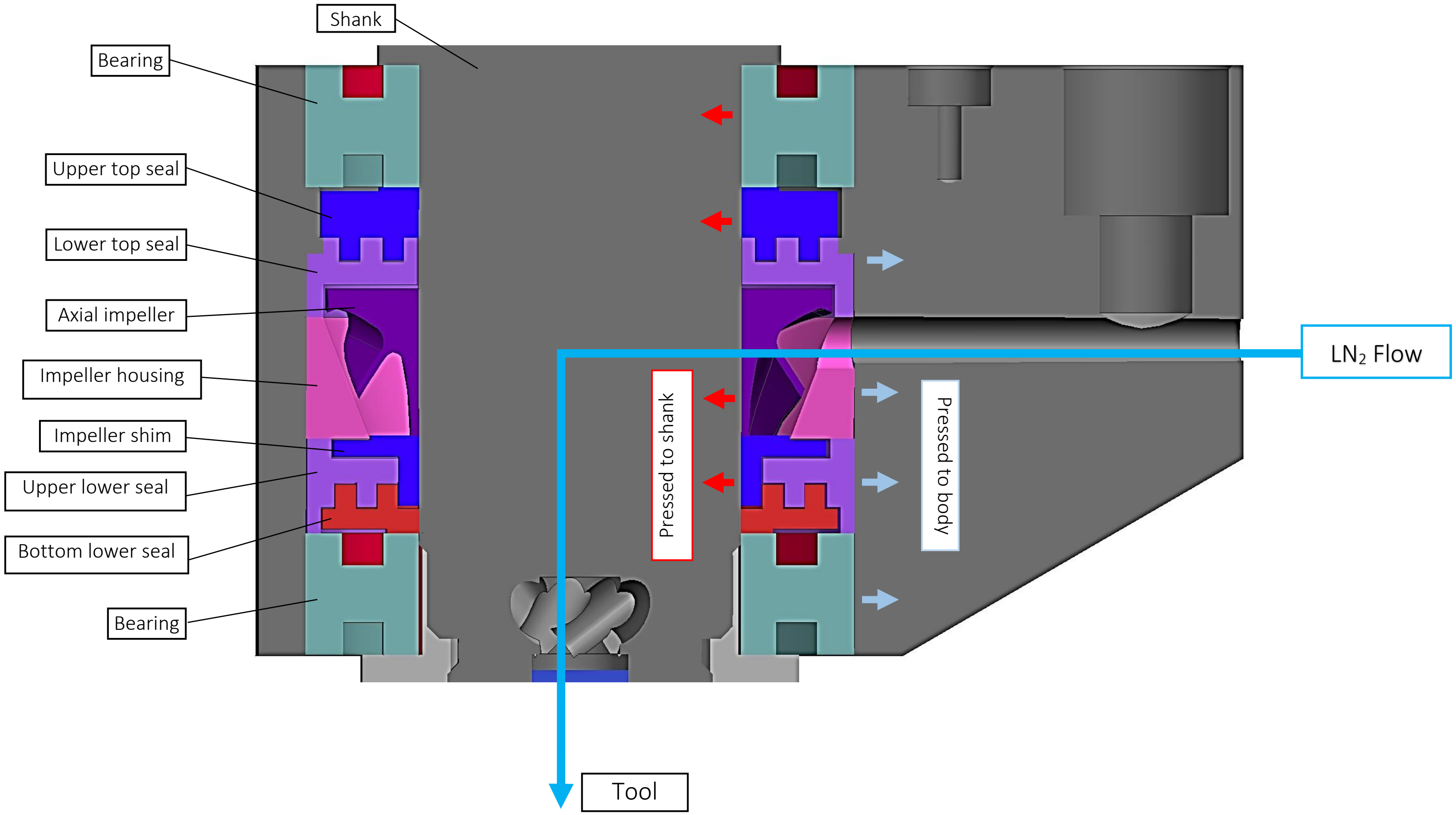
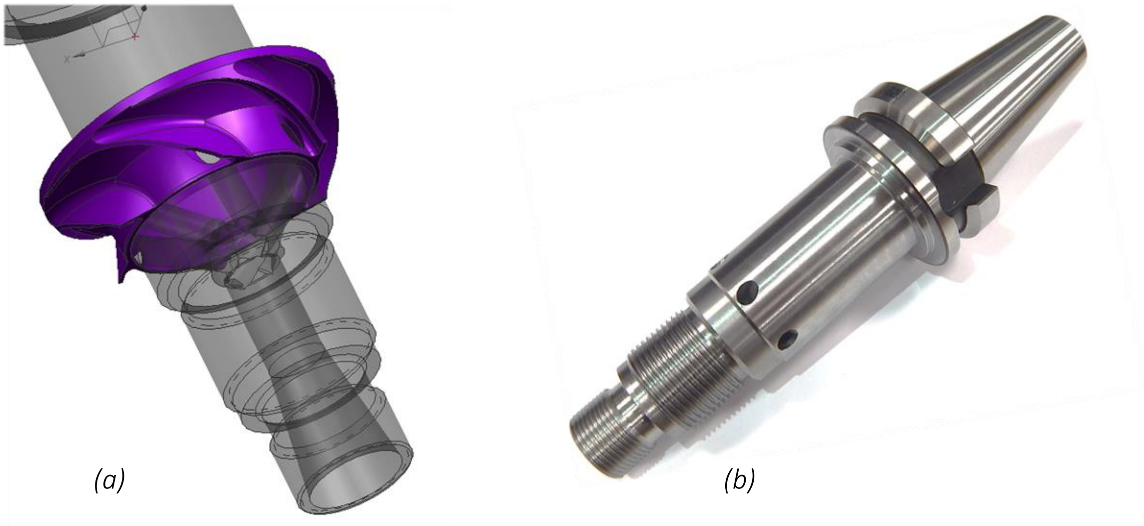


Figure 7-23 - Cross section of Iteration 3 internal components

III. Shank

A new shank was designed and manufactured to accommodate for the increased length required for the impeller. The coolant holes have been offset from the centre axis and are angled downwards at 45^0 to reduce the LN_2 travelling distance. Figure 7-24(a) demostrates how the impeller matches up to the coolant entry holes. The manufactured shank is shown in Figure 7-24(b).

Parts are pressed on to the shank. The final fitment is completed via tightening of an end cap on to a thread. This cap tightens on to a shoulder therefore giving a known position and length, ensuring ensure correct assembly.



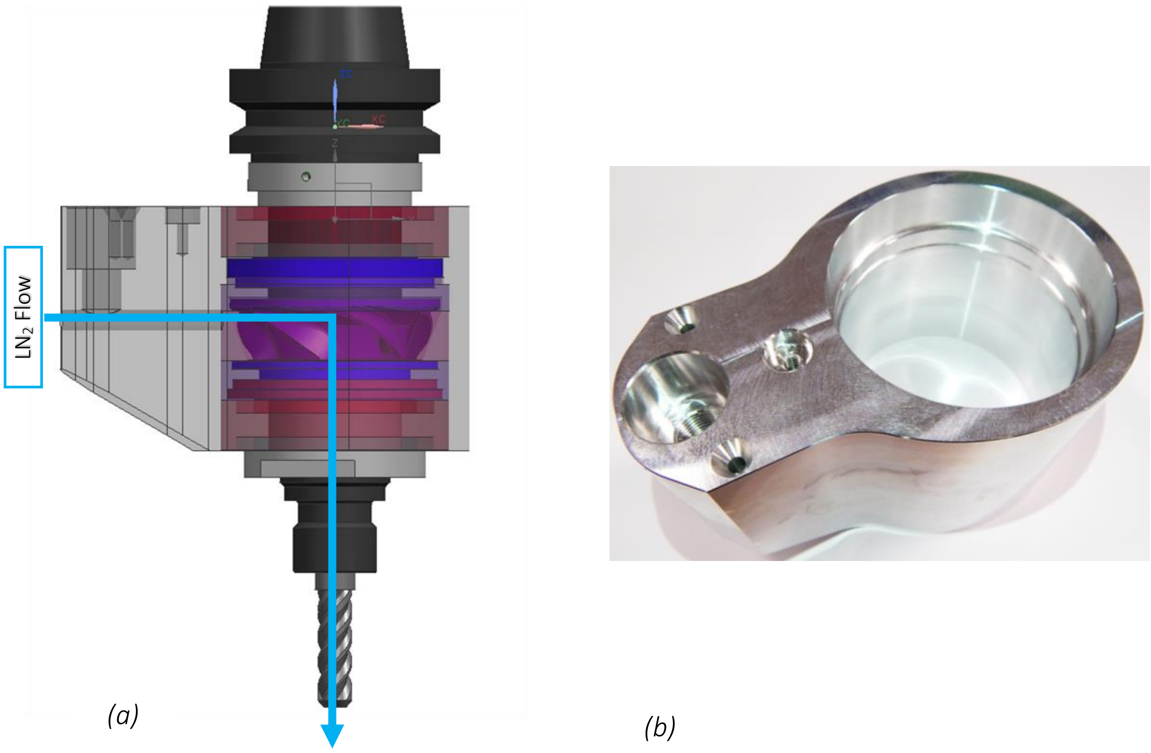
(a) *(b)*

Figure 7-24 – (a) CAD isometric view, (b) Finished part

IV. Body

A new inducer body has been designed by the author to facilitate the addition of the impeller and the increased shank length. Additively manufacturing the body for previous iterations allowed for an internal gallery that spans the circumference of the shank. The impeller is surrounded by a housing shown in Figure 7-23. This is used to form a space for LN_2 to expand in to before being redirected by the impeller vanes. Therefore, the internal gallery is no longer required and the body can be manufacturing using CNC machining methods. A conventional CNC manufacturing route is more scalable to large volume production and more cost efficient. Typical 'as built' additive components will only be accurate to ± 0.1mm and therefore require machining after being built to achieve the final shape, it is this machining that adds time and cost. Therefore, if the function of a part can be met through a standard CNC process it is preferable.

The re-designed body is shown below in Figure 7-25. The impeller and seal arrangement create an internal volume for the cryogen to flow into. Figure 7-25 shows a cutaway section of the assembly, the cryogen flow path is highlighted with an arrow. A complete parts breakdown is shown in Figure 7-26. Detailed engineering drawings are presented in appendix III.



(a) *(b)*

Figure 7-25 – (a) CAD body cutaway, (b) Iteration 3 body manufactured

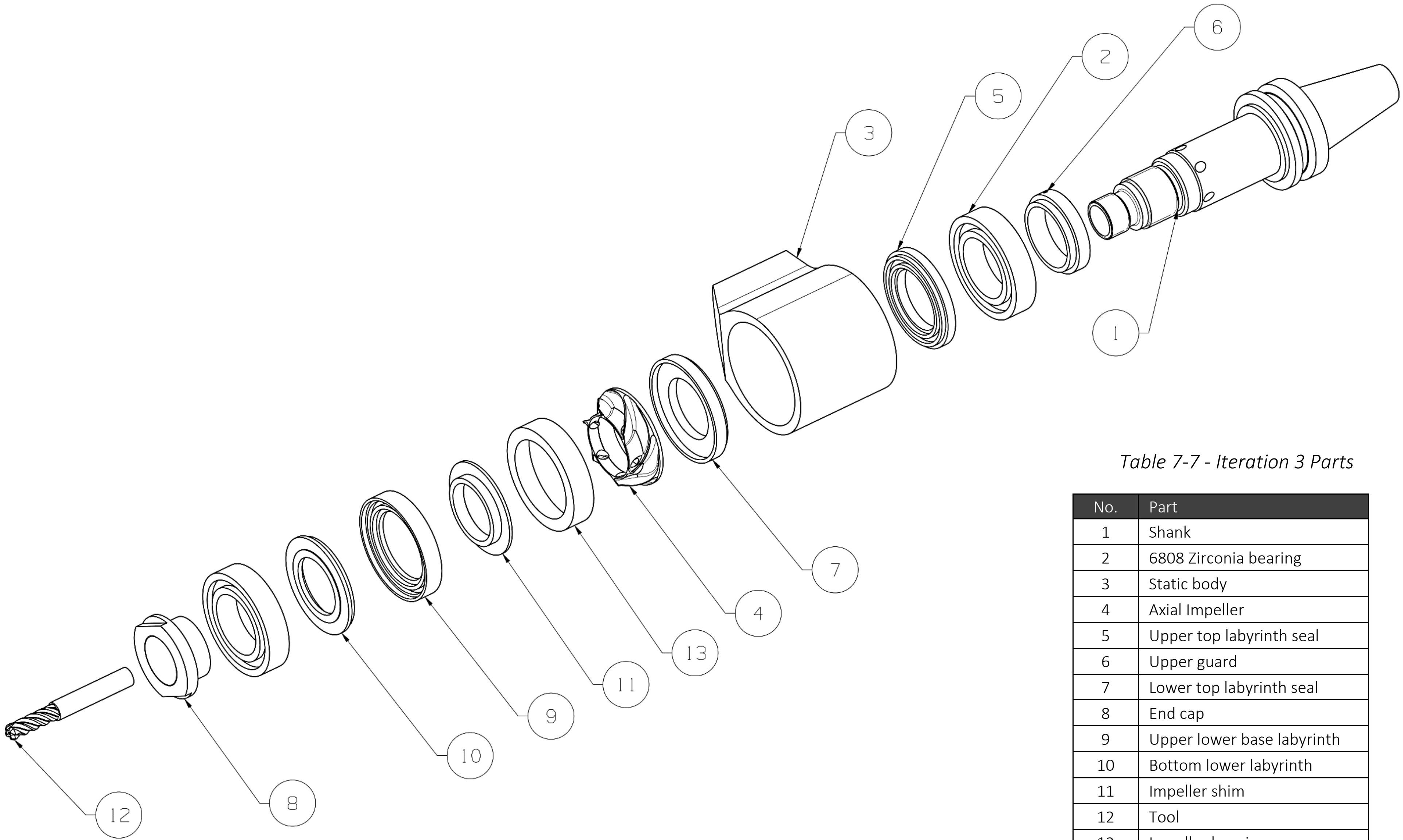


Figure 7-26 – Iteration 3 exploded assembly

Table 7-7 - Iteration 3 Parts

No.	Part
1	Shank
2	6808 Zirconia bearing
3	Static body
4	Axial Impeller
5	Upper top labyrinth seal
6	Upper guard
7	Lower top labyrinth seal
8	End cap
9	Upper lower base labyrinth
10	Bottom lower labyrinth
11	Impeller shim
12	Tool
13	Impeller housing

7.6.1 Iteration 3 – Testing

The test procedure detailed in Table 7-2 was followed. The inducer was connected to the Bridgeport spindle and rotated up to 3000 rpm without the use of LN_2. The rotation was stopped and the body and shank were checked for any signs of heat caused by friction. A flow of LN_2 was introduced into the inducer whilst rotating at 250 rpm. The system underwent a short gassing off period to cool down the inducer and shank to facilitate flow of LN_2. LN_2 was observed exiting the tool tip.

Towards the end of the gassing off stage, the inducer was increased in speed up to 500rpm. LN_2 was observed exiting the tool tip. The inducer was left running for 3 minutes with the LN_2 flowing. At the end of this period the spindle speed was gradually increased in 100rpm increments, in each instance holding for at least 30 seconds at that setting. At a rotational speed greater than approximately 400 rpm the inducer began to leak. Above 1100rpm, LN_2 was observed to be ejected from the inducer through leak paths with minimal LN_2 at the tool tip. The test was stopped at the spindle speed of 2500 rpm. The main observations are recorded in Table 7-8.

Table 7-8 - Iteration 3 testing observations

Spindle speed (rpm)	Observations
250	Good LN_2 flow from tip.
500	LN_2 flow reduced. Vapour leaks becoming visible.
750	LN_2 flow approximately observed to be half of starting strength. Leaks flow rate increased.
1000	LN_2 flow reduced further. Leaks visibly creating large vapour plumes.
1100	All LN_2 observed to be exiting inducer through leak paths.
2500	No LN_2 flow to be observed leaving the tool tip - only being ejected from inducer between shank and body.

The inducer ran smoothly at 2500 rpm, no LN_2 was observed exiting the tool tip. It was decided to machine a billet of Ti–6Al–4V using a spindle speed of 1000rpm. Figure 7-27 shows the inducer during the machining of a billet 100mm in length. In total 9 passes were performed across the billet. In Figure 7-27 a large quantity of condensed ice can be observed on the surface that has condensed from the surrounding atmosphere. The inducer was afterwards removed for disassembly and inspection.

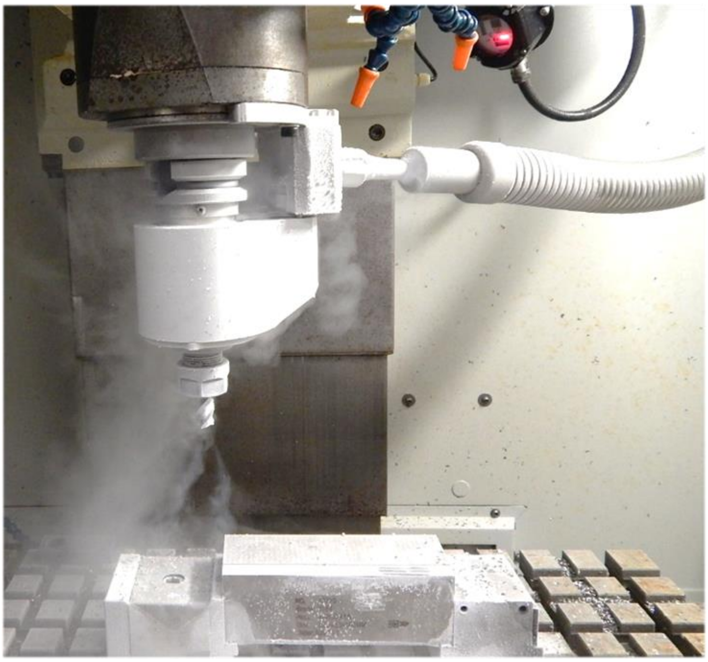


Figure 7-27 - Stationary after a cutting pass

7.6.1 Iteration 3 – Technical review

A third iteration of the cryogenic coolant inducer has been designed and manufactured. A machining test has been performed on a billet of Ti-6Al–4V.

Above a spindle speed of 400 rpm LN_2 began to escape through leak paths from the upper and lower halves of the inducer. The vapour flow from the leaks increased with rotational speed. The cut-off point at which the flow became insignificant was 1100 rpm versus 750 rpm for iteration 2 and 500 rpm as seen in the first iteration. Through use of an axial impeller and redesigned vertical labyrinth seals, the spindle speed at which LN_2 ceased to flow from the tool tip has doubled.

The inducer was disassembled for inspection. The PDS identified a requirement for the inducer to be easily dissembled without the need for special tooling which was satisfied by iteration 3. The inducer can be loaded and unloaded from the Bridgeport spindle without difficulty of obstruction. Changing cutting tools was a simple process due to the adoption of the ER collet system. Standard ‘off the shelf’ carbide tooling was used.

All parts were visually inspected for signs of wear for which no obvious markers were found.

Based upon the findings of the testing of iteration 3, the inducer has only partly satisfied the main mechanical requirement of delivering LN_2 to the cutting zone. Using this design, machining of components will only be possible at low spindle speeds where LN_2 was actively seen to be flowing from the tool. The developed inducer is therefore only suitable for use up to 1000 rpm or less with a 12mm diameter cutter.

8 Discussion

This chapter discusses the literature review, design methodology, design and manufacture of a cryogenic coolant inducer.

I. Literature review

A thorough literature review was conducted on machining of difficult to machine materials. It was found that common approach of using flood coolants in industry suffer from many disadvantages, poor machining performance, high costs, environmental and health concerns (Klocke and Eisenblätter, 1998; Shokrani, Dhokia and Newman, 2012). The costs are often underestimated in industry as they are commonly considered as overhead costs and are not considered part of equipment maintenance and disposal (Shokrani, Dhokia and Newman, 2012, 2014). Using LN_2 as a coolant during machining was found to offer clear benefits for use with difficult to machine material by Hong et al. (2001). It was found that LN_2 offers health and environmental advantages (Soković and Mijanović, 2001; Pusavec *et al.*, 2010; Shokrani, Dhokia and Newman, 2012). The state-of-the-art in cryogenic machining, both in industry and research was also reviewed. A research gap was identified for a solution that would enable cryogenic machining in three or more axis machining centres that could be retrofitted to most existing machine tools without the need for extensive modification or the purchase of a new machine.

II. Design methodology

A methodology for the design of a cryogenic inducer was implemented based on an adaptation of the total design approach (Pugh, 1991; Burge, 2009). The final methodology is shown Figure 5-2, using a flow chart adapted from the Pahl and Beitz systematic design model (Pahl *et al.*, 2007; Cross, 2008; Kannengiesser and Gero, 2015).

Using the adapted methodology, the requirements for a cryogenic inducer were captured in a PDS, detailed in 6.1. Weighted selection was used to determine the concept that would best satisfy the requirements.

The black box approach was used to identify the system functions and to create components. Figure 6-2 shows a development of this model where different paths were identified for transporting and directing LN_2 to the cutting zone. Using this model, four concept variants were generated that satisfied the black box functional requirement and PDS. A Pugh weighted selection was used where certain qualities and outcomes were assigned numerical values. Using these values and qualitative reasoning the concept of using a through tool coolant inducer was selected. An FMEA was used to identify design risks and failure modes. The FMEA consistently identified sealing as being the most common barrier to correct operation of the inducer, which was proven during testing.

It was estimated that by designing parts for low temperature operation these problems could be avoided, however, the extent of the dual state flow of the LN_2 was not fully considered. When LN_2 was introduced to the inducer, there was a delay between switching on and observation of liquid flow from the tool. This was due to the flow path components (valves, vacuum insulated line and inducer) cooling down to facilitate liquid flow. Visible steam pressure spikes were observed to be exiting the tool tip during this time. It is believed that this was due to the LN_2 boiling within the vacuum insulated line and inducer. Fluid properties inherent to nucleating liquefied gases should be considered for future design. After selecting the coolant inducer concept, an existing unit specifically designed for use with flood coolant was acquired. This was broken down and analysed to identify parts and functions. It was decided to manufacture a new body and seals to fit onto the original shank to test the concept. This was highly beneficial in providing design points for the first iteration of the cryogenic machining inducer. Bearings were sourced that could withstand cryogenic temperatures.

III. Concept design

Through following the design methodology outlined in chapter 4, a first design was generated, then iterated to add in design changes highlighted through testing. Through weighted selection, a coolant inducer concept was found to satisfy the PDS.

The major design consideration was identified early on through the black box function model as the transporting of LN_2 form a static line through a rotational union in to the centre of a rotating shaft. From there it would be directed downwards into the tool.

By using additive manufacturing, a titanium body was designed specifically for LN_2 to receive coolant from a vacuum insulated line and direct it in to the shank. The novel approach to manufacturing allowed for an internal gallery for the LN_2 to flow into before being redirecting it into the rotating shank.

The FMEA identified the sealing as a high-risk failure mode. Labyrinth seals were selected as a potential solution. These are non-contact that maintain a pressure boundary through use of a torturous path for the fluid to escape through. Horizontal fins were used at first, followed by a change to vertical ones after testing. A sequential test procedure was established and is shown in Table 7-2. Each test had to be successful to proceed to the next. This was both for safety requirements and to prevent damage to equipment. Design changes were fed back into iteration two where vertical labyrinth seals were introduced; these presented an improvement but the leaks from the shank and body union were still causing a failure at higher spindle speeds.

Three iterations of labyrinth seals were developed. Machining at a high spindle speed greater than 1000 rpm was unsuccessful due to leakage.

IV. Generated solution – final design

The final iteration used an additively manufactured impeller. This had the function of changing the velocity components of LN_2 flowing from the static vacuum line. A new labyrinth seal arrangement was implemented.

The developed concept has shown that the approach of using a cryogenic inducer to cool the cutting process is feasible. Manufacturers are currently limited to purchasing retrofit spray nozzles (whereby certain tools and features such as pocket milling will be limited or not possible) or a new machine tool (at great expense). A cryogenic inducer would allow a manufacturer to machine existing parts including those with deep pockets and hole drilling whilst utilising existing machine tools.

The inducer satisfied the requirement of delivery a flow of liquid LN_2 to the tool tip. The flow reduced with an increase in spindle speed, cutting off at approximately 1000 rpm. The LN_2 was observed to be leaking from the top and bottom of the body, from between the seals. The pressure relief valve on the Dewar did not release at any point. LN_2 is entering the body and leaking through the seals, therefore not enough pressure is being exerted upon the LN_2 to force it in to the rotating shank.

The seals require further development to increase the sealing pressure against the rotational force from the shank. Using a larger shank standard (e.g. CAT50) would allow for larger labyrinth seals to be used. The greater sealing area would aid the pressure exerted on the LN_2. Using larger cutting tools (such as insert based cutters) would result in the surface cutting speed being achieved at a slower rotational speed, reducing the rotational forces acting on the LN_2.

A billet of Ti-6Al-4V titanium alloy was machined with the inducer, 9 passes were performed across the billet at a cutting depth of 1mm.Figure 8-1 below shows iteration 3 being used to machine a machining a billet of Ti–6Al–4V.

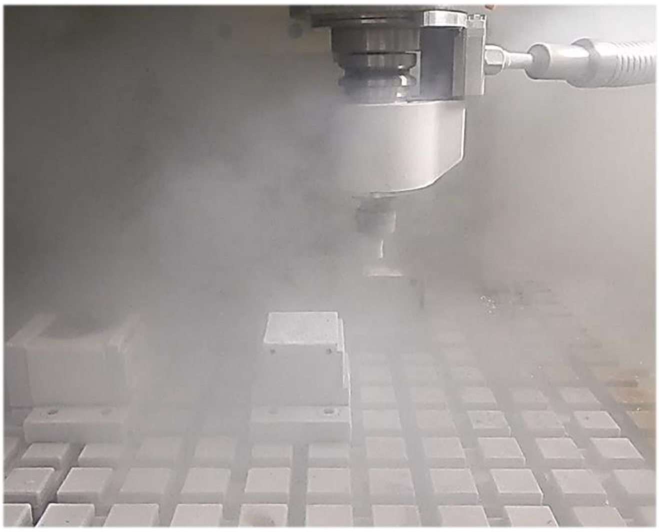


Figure 8-1 – Iteration 3 machining a billet of Ti–6Al–4V

9 Conclusions & Further Work

This chapter presents a series of conclusions that have been derived from the discussion. Shortfalls from the original PDS were identified in the discussion, further work is suggested that would advance knowledge in this area.

9.1 Conclusions

- A method for delivering LN_2 to the tip of a standard carbide cutting tool has been developed that can be retrofitted to machining centres whilst avoiding modifications to the spindle.

- The developed cryogenic coolant inducer was used to successfully complete machining passes on a billet of Ti-6Al-4V at a rotational spindle speed of 1000 rpm.

- Through an iterative design approach, the spindle speed at which LN_2 ceased to flow from the tool tip was increased from 500 to 1000 rpm.

- A literature review was undertaken that has shown that there is a benefit to using LN_2 when machining difficult to machine materials such as Ti-6AL-4V, Inconel 718 and Cobalt Chrome. It was found that providing a spray of LN_2 into the cutting zone can lead to an increase in tool life, faster machining speeds and improved surface finish.

- The literature review identified a market gap for a system to enable cryogenic machining using LN_2 including the ability to machine pocketed features and holes in three or more axis machining centres that could be easily retrofitted without the need for extensive modification or the purchase of a new machine tool.

- By specifying a different shank standard, the inducer can be produced for a large majority of machine tools. The design is easily retrofitted onto a large variety of mills as the tool blank can easily be chosen or scaled as other standards, for instance HSK63, CAT50 and CAPTO.

- Existing 'off the shelf' through-tool coolant cutters can be used allowing greater flexibility for tooling choice. Specialised cutting tools are not required to be developed.

9.2 Further work

The suggested modifications and areas of work are as follows:

I. Investigating the flow of LN_2

It is unknown at what point in the inducer or the vacuum insulated line the LN_2 changes from purely liquid to a dual-state flow. It is unknown how much is caused by heating from the surroundings and from turbulence generated within the inducer.

II. Analysis and optimisation of turbine vane geometry

Optimisation would improve the redirection of the velocity components of the LN_2 from the vacuum line more effectively. This would lead to an increased pressure and flow rate at the tool tip.

III. Further analysis and development of seals

The third iteration seals enabled the inducer the reach a spindle speed of twice that from the first iteration before the flow of LN_2 to the tool tip stopped. Modelling of fluid flow between the seals would further inform upon the design. Increasing the sealing area would aid maintaining the pressure across the seals. This can be done by increasing the diameter of the body, or by increasing the number of fins.

IV. Investigate other materials

Materials with low CTE values are desirable for creating components that would not would contract less during use with LN_2. In components where thermal contraction has been identified as affecting their function alternative materials should be investigated. Invar is an example of a material with a low CTE.

V. Increasing the size of the cryogenic inducer

Using a larger shank standard (e.g. CAT50) would allow for larger diameter shank and tooling allowing for a sealing with larger area Larger diameter tools also have the benefit of typically requiring a lower spindle speed during cutting operations. The flow rate of the LN_2 exiting the tool would be greater due to the decreased rotational force acting upon it by the rotational forces.

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Appendix I – CES materials properties of unified polymers

	PAI (unfilled)	FEP (unfilled)	PFA (unfilled)	PI (unfilled)	PTFE (unfilled)
Composition overview					
Material family	Plastic (thermoplastic, amorphous)	Plastic (thermoplastic, semi-crystalline)	Plastic (thermoplastic, semi-crystalline)	Plastic (thermoplastic, amorphous)	Plastic (thermoplastic, semi-crystalline)
Base material	PAI (Polyamide-imide)	FEP (Fluorinated ethylene propylene)	PFA (Perfluoroalkoxyethylene)	PI (Polyimide, aromatic)	PTFE (Polytetrafluoroethylene)
Polymer code	PAI	FEP	PFA	PI	PTFE
Composition detail (polymers and natural materials)					
Polymer (%)	100	100	100	100	100
Price					
Price (GBP/kg)	34.4 - 36.5	17.4 - 20	16.6 - 22.7	29 - 31.5	11.2 - 12.8
Price per unit volume (GBP/m^3)	48200 - 52900	36900 - 43500	35200 - 49200	38600 - 44900	24000 - 28100
Physical properties					
Density (kg/m^3)	1400 - 1450	2120 - 2170	2120 - 2170	1330 - 1430	2140 - 2200
Mechanical properties					
Young's modulus (GPa)	4.78 - 5.02	0.336 - 0.353	0.471 - 0.495	2.07 - 2.76	0.4 - 0.552
Yield strength (elastic limit) (MPa)	38 - 42	14.9 - 17.1	13.8 - 15.2	86.2 - 89.6	19.7 - 21.7
Tensile strength (MPa)	182 - 202	18.6 - 21.4	27.6 - 29.6	72.4 - 118	20.7 - 34.5
Elongation (% strain)	13.9 - 16.1	250 - 330	279 - 323	7.5 - 90	200 - 400
Compressive modulus (GPa)	3.9 - 4.1	0.336 - 0.353	0.471 - 0.495	2.17 - 2.41	0.402 - 0.423
Compressive strength (MPa)	210 - 230	14.4 - 15.9	23 - 25.3	125 - 276	11.2 - 12.3
Flexural modulus (GPa)	4.88 - 5.12	0.55 - 0.653	0.653 - 0.825	2.48 - 3.44	0.537 - 0.564
Flexural strength (modulus of rupture) (MPa)	228 - 252	26 - 30	38.6 - 41.4	90.5 - 199	29 - 48.3
Shear modulus (GPa)	1.65 - 1.73	0.117 - 0.122	0.164 - 0.172	0.74 - 0.987	0.138 - 0.19
Shear strength (MPa)	122 - 134				
Bulk modulus (GPa)		0.949 - 0.997	1.21 - 1.27	3.84 - 4.03	1.53 - 1.6
Poisson's ratio	0.44 - 0.46	0.432 - 0.45	0.426 - 0.443	0.391 - 0.407	0.44 - 0.46
Shape factor	9.42	3.6	4.3	4	3.7

Mechanical properties					
Hardness - Vickers (HV)	11 - 13	5	4 - 6	26 - 27	6 - 7
Hardness - Rockwell M	105 - 115	29 - 31		91 - 100	
Hardness - Rockwell R	120 - 130	40 - 50		123 - 135	
Hardness - Shore D					55 - 60
Fatigue strength at 10^7 cycles (MPa)	73 - 81	7.02 - 9.12	10 - 13	45 - 50	5.75 - 7
Mechanical loss coefficient (tan delta)	0.008 - 0.00832	0.113 - 0.119	0.0808 - 0.0849	0.0145 - 0.0193	0.0725 - 0.1
Impact & fracture properties					
Fracture toughness (MPa.m^0.5)	3.68 - 4.48	1.49 - 4.18	1.2 - 3.59	2.16 - 6.4	1.32 - 1.8
Ductility index	0.95 - 1.16	101 - 123	111 - 136	0.26 - 0.32	2.09 - 2.55
Impact strength, notched 23 °C (kJ/m^2)	13.3 - 14.7	590 - 600	590 - 600	7.9 - 9	15 - 17
Impact strength, notched -30 °C (kJ/m^2)				6.36 - 7.7	
Impact strength, unnotched 23 °C (kJ/m^2)	90.9 - 110	590 - 600	590 - 600		
Thermal properties					
Melting point (°C)		264 - 286	300 - 310	375 - 401	315 - 339
Glass temperature (°C)	264 - 286	81 - 96	105 - 112	240 - 260	117 - 130
Heat deflection temperature 0.45MPa (°C)	278 - 340	119 - 161	54 - 87	263 - 385	71 - 121
Heat deflection temperature 1.8MPa (°C)	250 - 306	49 - 82	30 - 61	307 - 360	31 - 62
Maximum service temperature (°C)	200 - 220	196 - 215	250 - 271	221 - 241	250 - 271
Minimum service temperature (°C)	-195 - -185	-205 - -195	-205 - -195	-248 - -238	-268 - -200
Thermal conductivity (W/m.°C)	0.25 - 0.27	0.242 - 0.261	0.242 - 0.261	0.0963 - 0.176	0.242 - 0.261
Specific heat capacity (J/kg.°C)	994 - 1030	1010 - 1050	1020 - 1060	1390 - 1450	970 - 1090
Thermal expansion coefficient (µstrain/°C)	29.8 - 31.4	83 - 105	120 - 130	81 - 101	120 - 170

Appendix II – Detailed Engineering drawings of iteration 3

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& APPLY BEFORE FINISHING TOL. ±0,25 ANGLES ±2°
REMOVE SHARP CORNERS - CHAMFER OR R0,5 MAX.
INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

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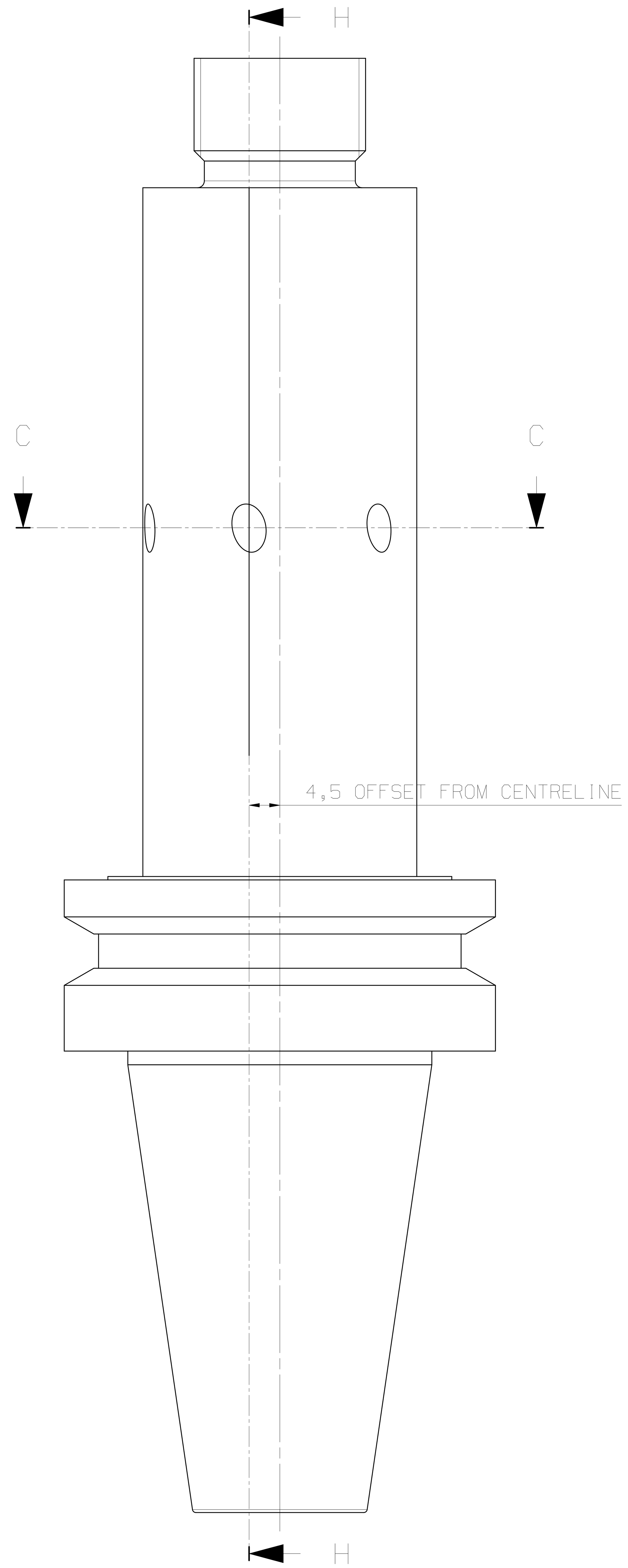

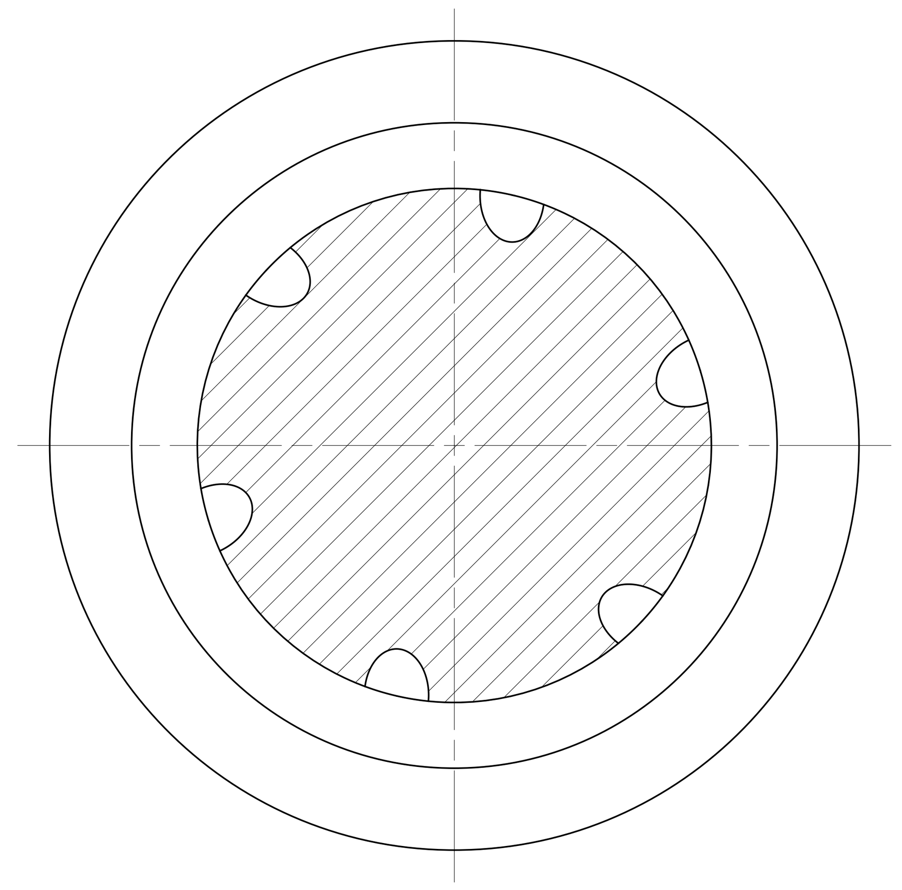

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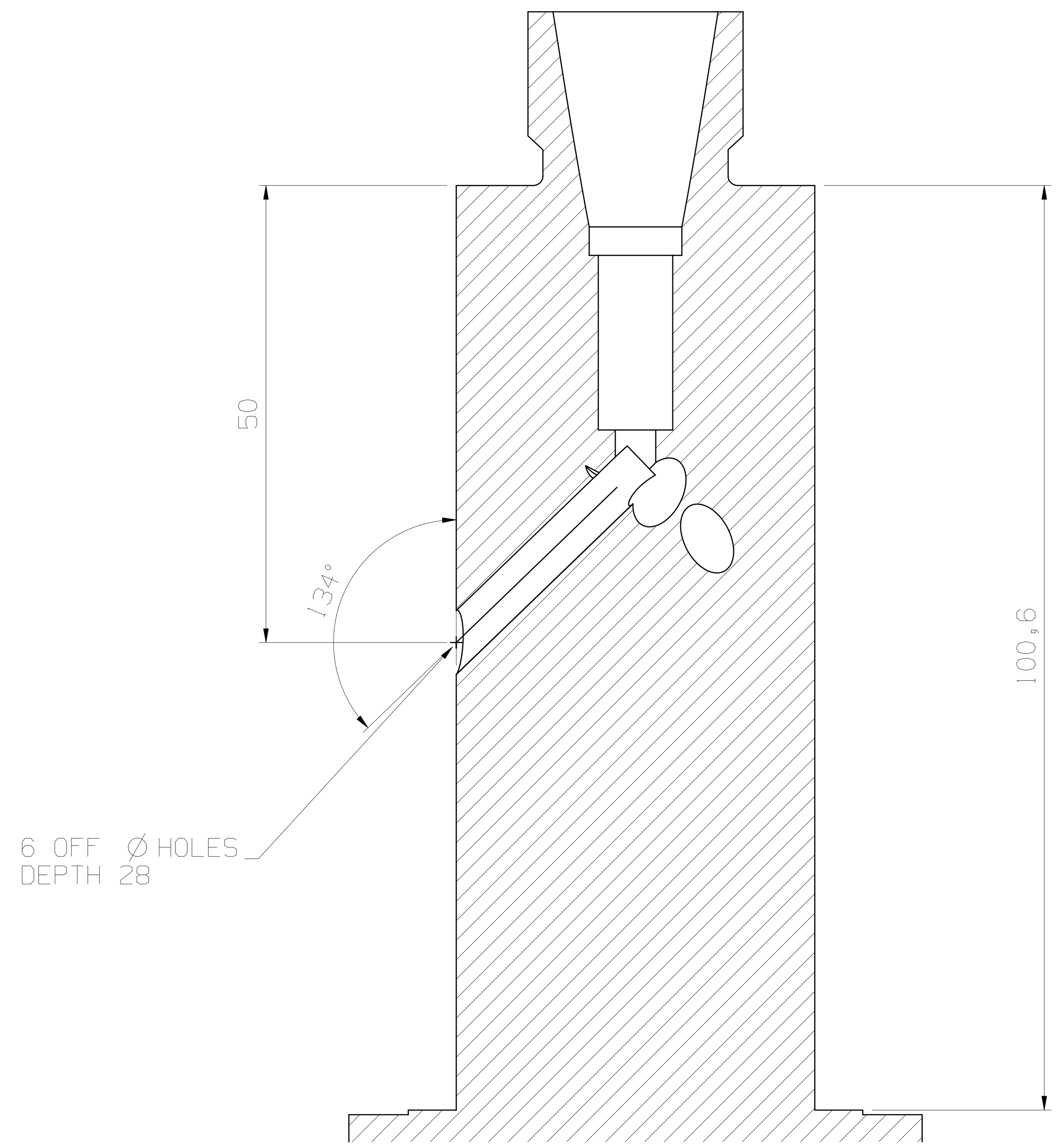

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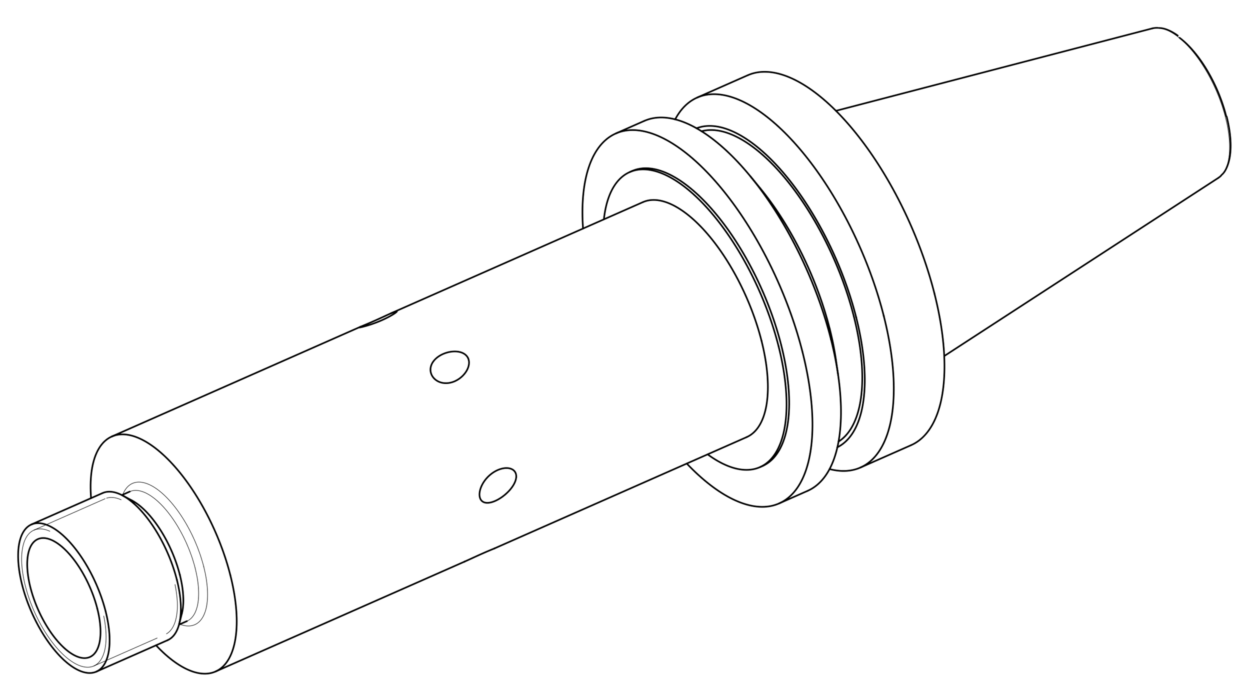

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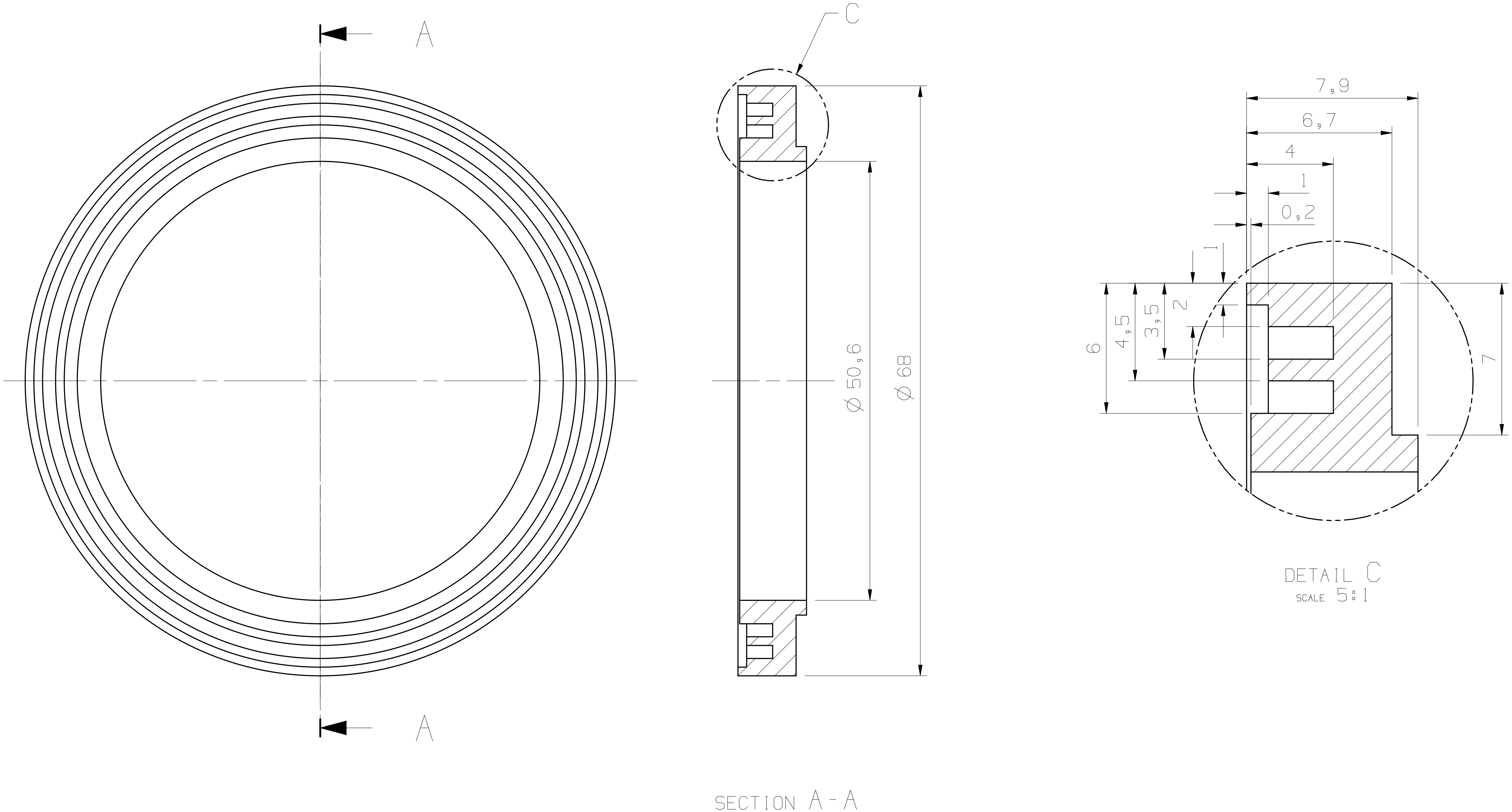

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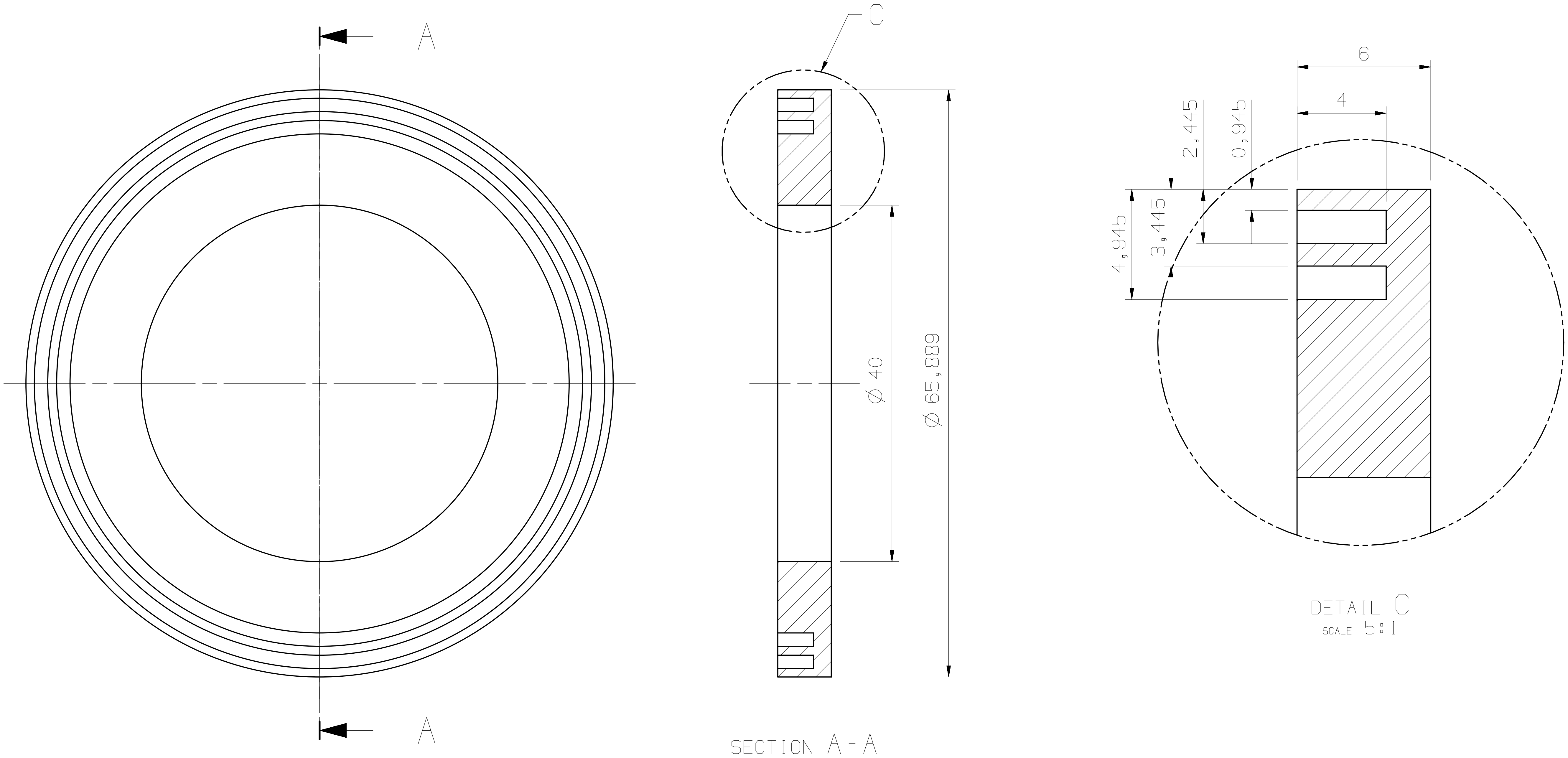

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SEE DESIGN STANDARD DS520 FOR DEFINITION OF R & FP No.
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INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

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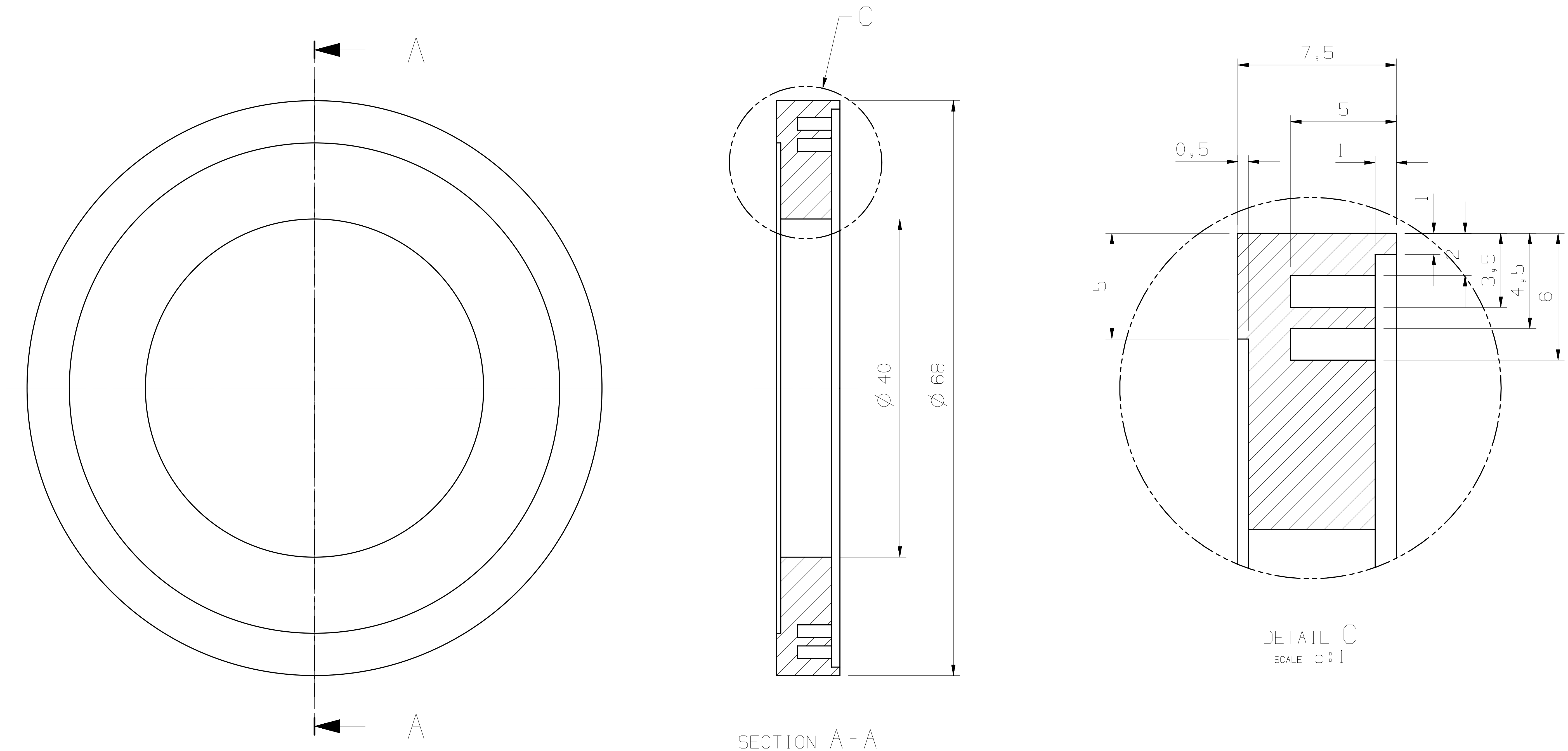

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3rd ANGLE PROJECTION

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INTERNAL CAP - UPPER

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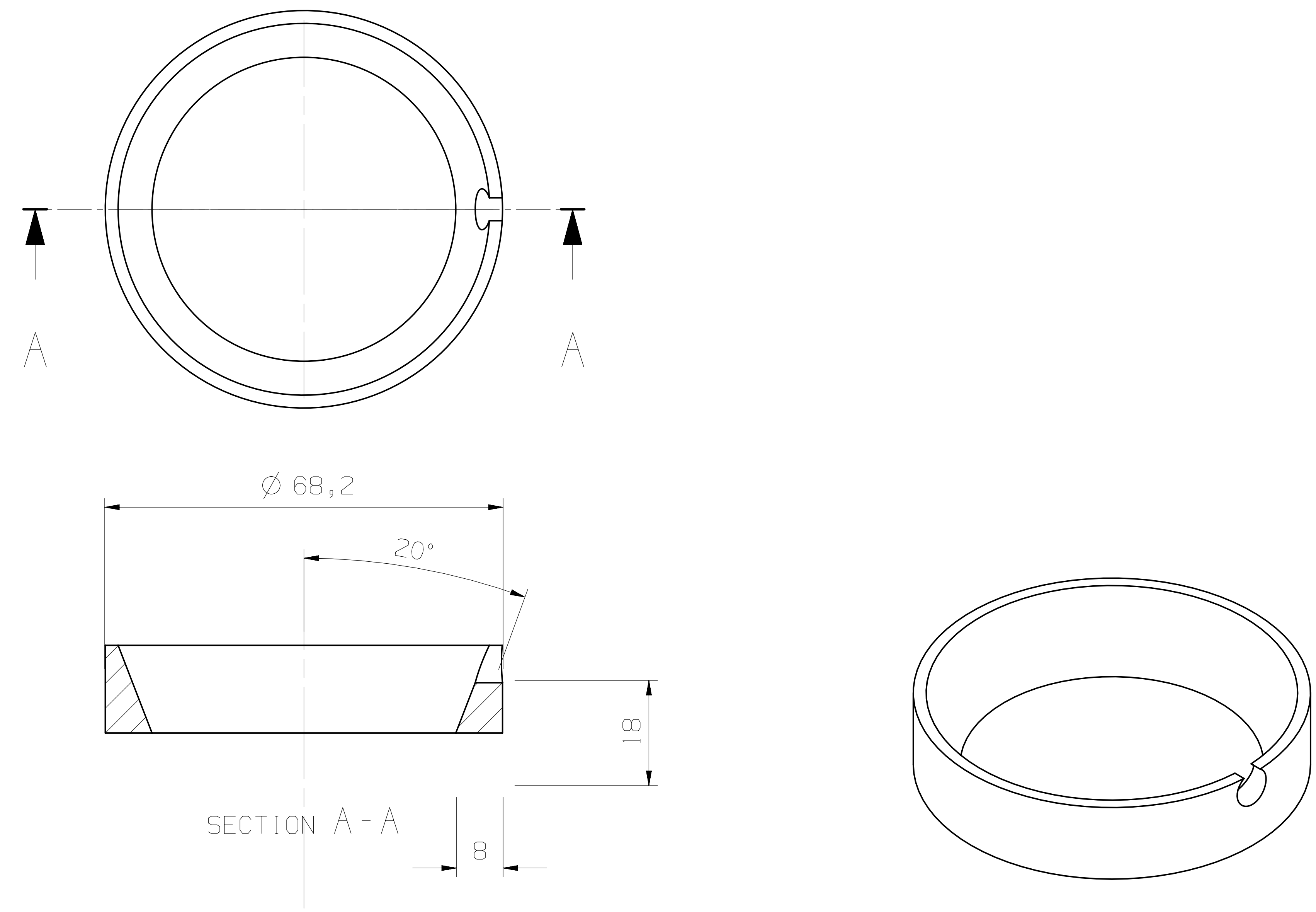

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INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - √Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

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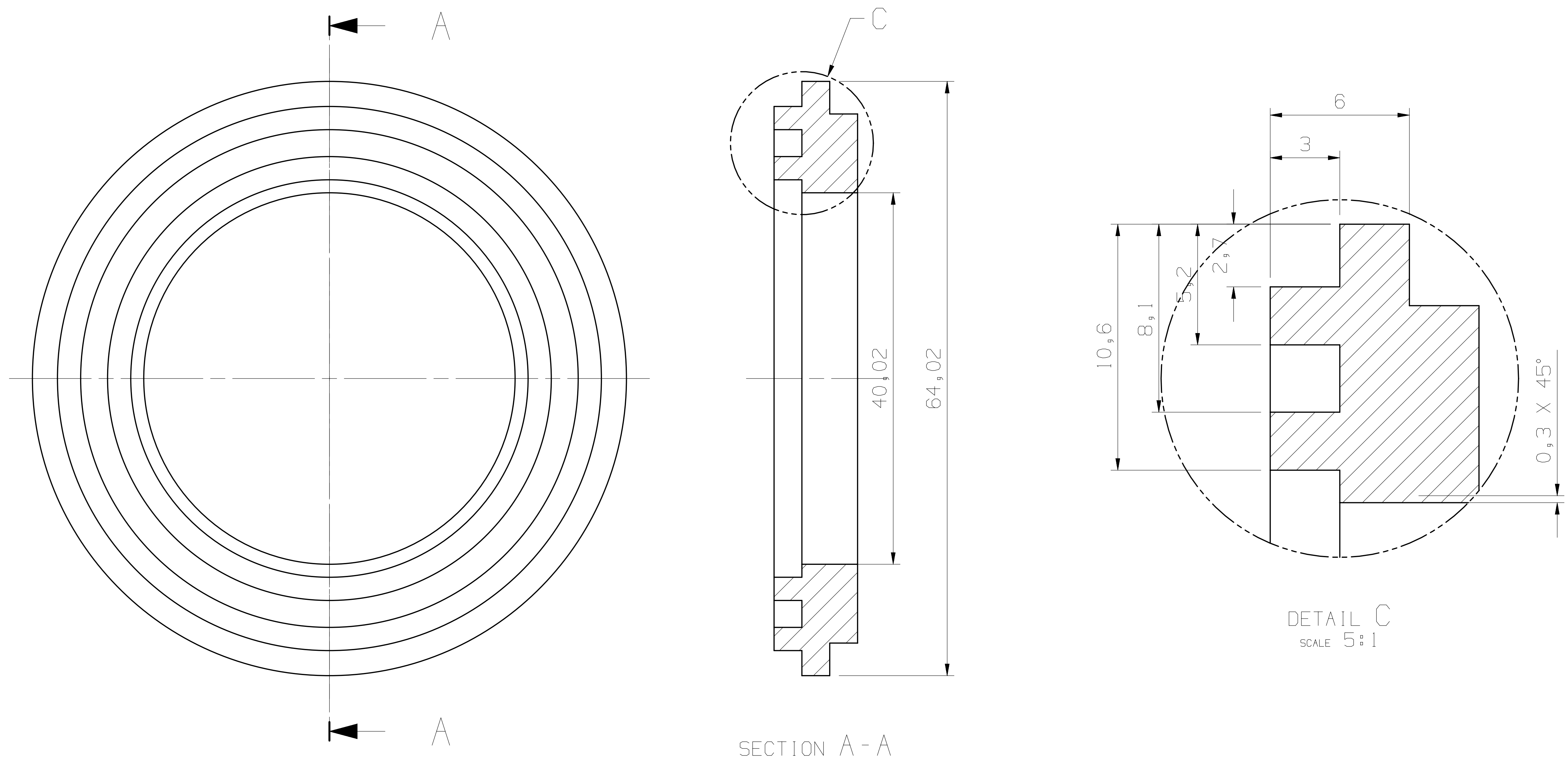

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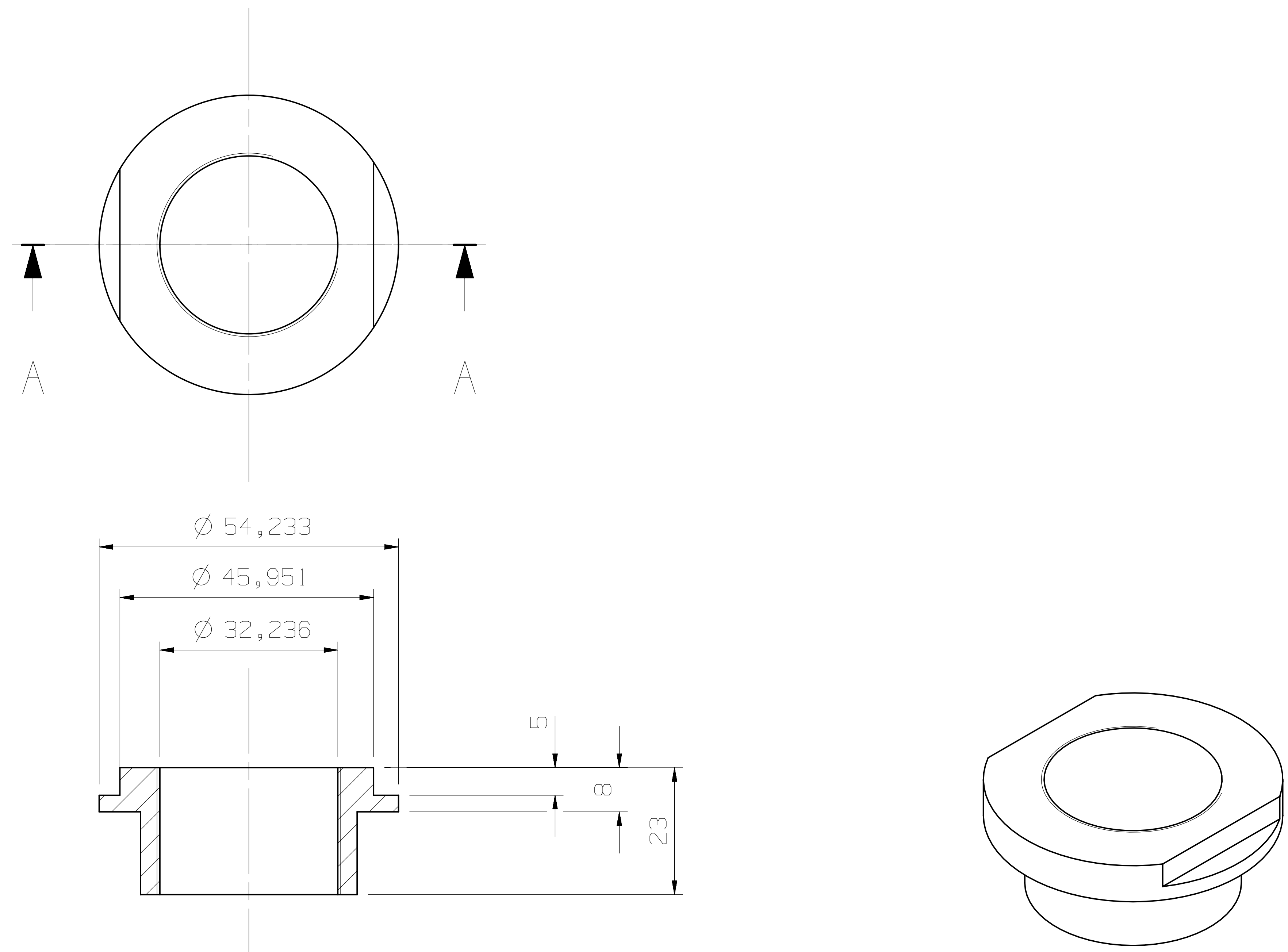

SECTION A-A

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3rd ANGLE PROJECTION

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BEARING SUPPORT RING

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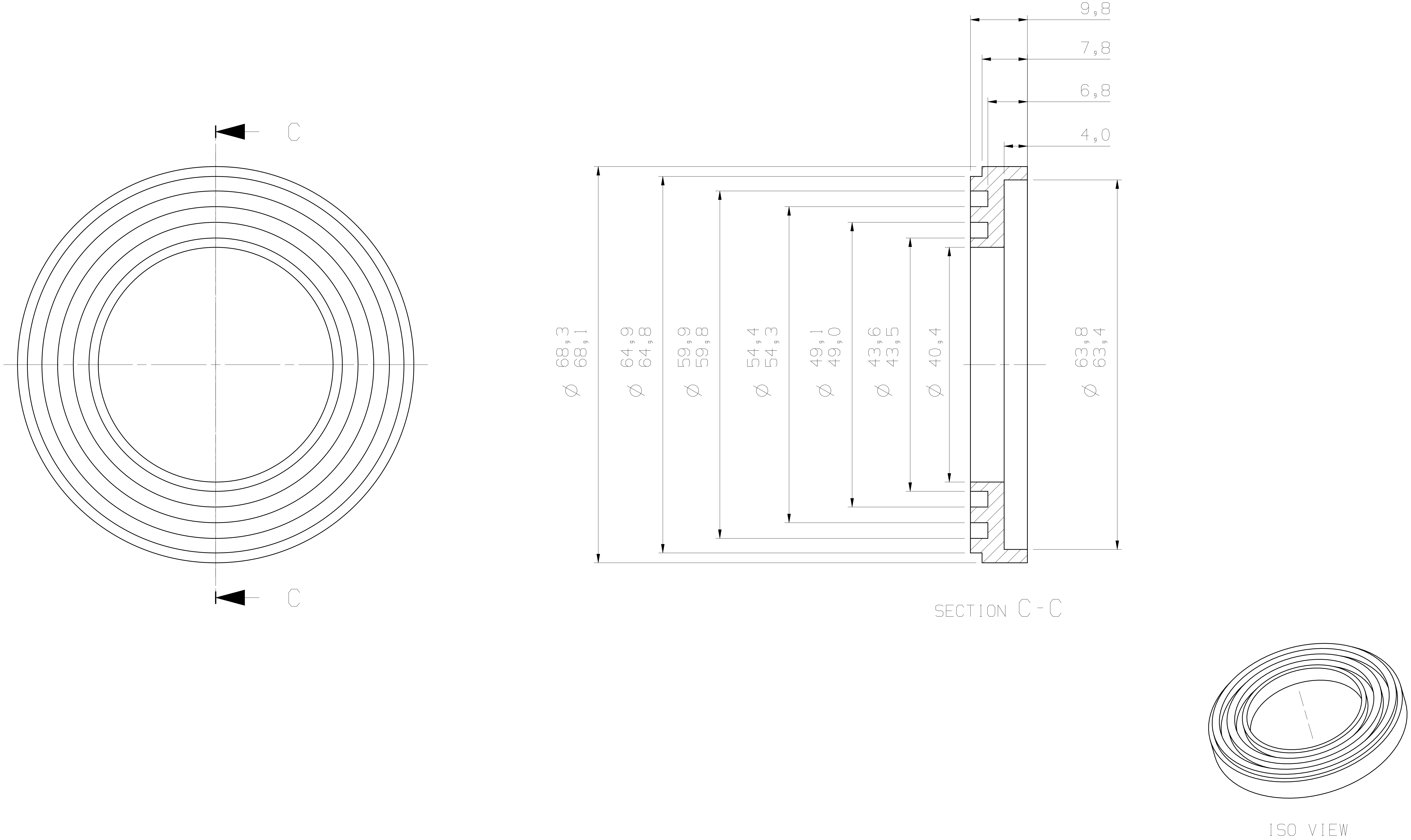

SEE DESIGN STANDARD DS336 FOR DEFINITION OF △ SYMBOL.
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REMOVE SHARP CORNERS - CHAMFER OR R0,5 MAX.
INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

DO NOT SCALE

TITLE	DRAWN BY	DRAWN DATE	SHEET	CHECKED
UPPER BODY RING	DW	SEP 15	1 OF 1	SH

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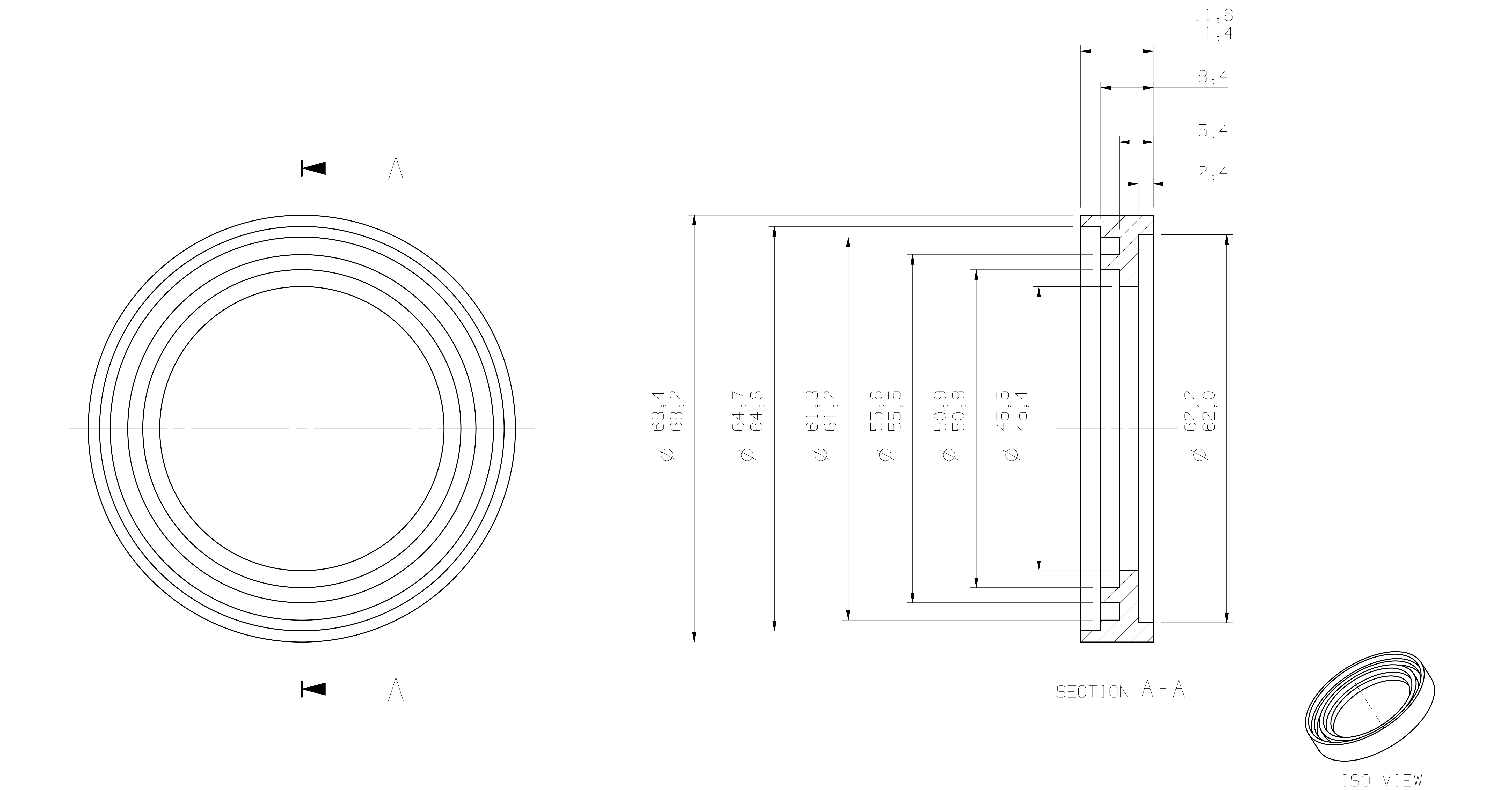
SCALE U.O.S. 2:1

DRAWING No. G-5858-7002-01-A



SEE DESIGN STANDARD DS336 FOR DEFINITION OF (C) SYMBOL.
SEE DESIGN STANDARD DS520 FOR DEFINITION OF R & FP No.
UNLESS OTHERWISE STATED: ALL DIMENSIONS IN MILLIMETRES & APPLY BEFORE FINISHING TOL. ±0,25 ANGLES ±2°
REMOVE SHARP CORNERS - CHAMFER OR R0,5 MAX.
INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

DO NOT SCALE

TITLE: TOOL SHANK SEAL

DRAWN BY	DRAWN DATE	SHEET	CHECKED
DW	SEP 15	1 OF 1	SH

RENISHAW MATL R CODE

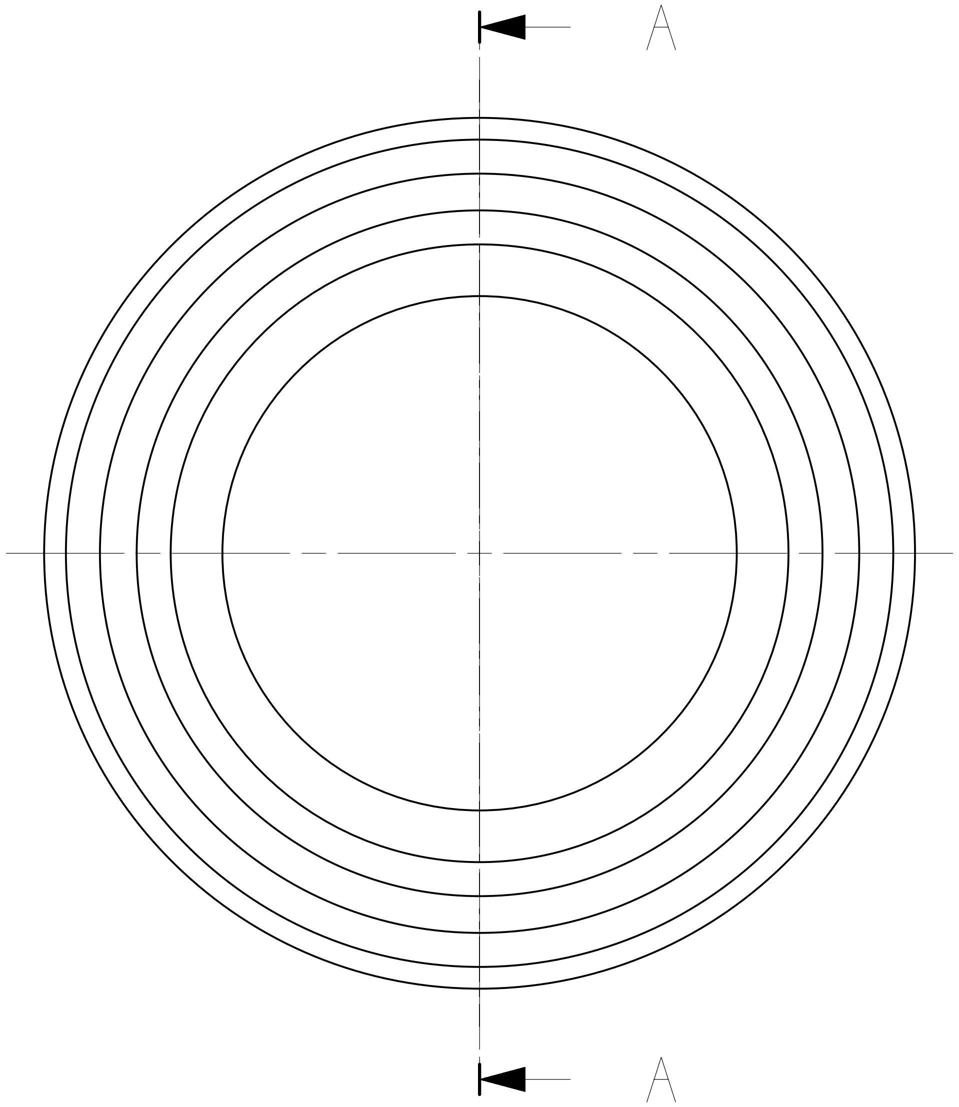
MATERIAL (ENTER R OR FP CODE TO VIEW EQUIVALENT MATERIAL SPEC USING SUPPLIER PORTAL SITE @ WWW.RENISHAW.COM)
PTFE NATURAL UNFILLED - MATERIAL ATTACHED WITH DWG

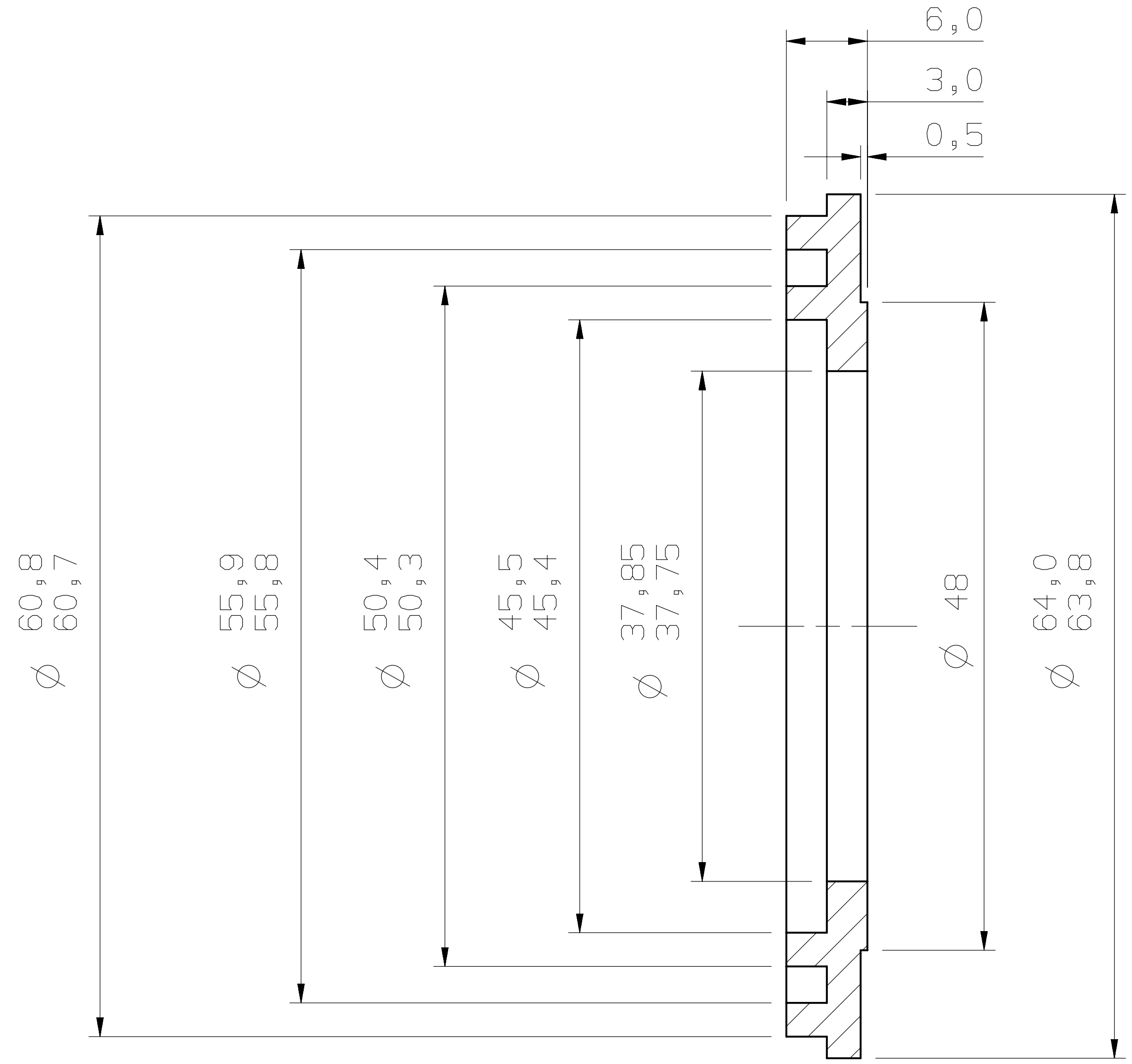
RENISHAW®

Wotton - under - Edge
Glos. England.
GL12 8JR

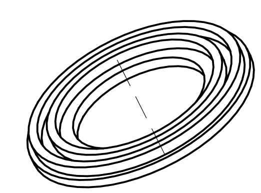
SCALE U.O.S. *:*

DRAWING No. G-5858-7004-01-A





SECTION A-A



ISO VIEW

SEE DESIGN STANDARD DS336 FOR DEFINITION OF △ SYMBOL.
SEE DESIGN STANDARD DS520 FOR DEFINITION OF R & FP No.
UNLESS OTHERWISE STATED: ALL DIMENSIONS IN MILLIMETRES & APPLY BEFORE FINISHING TOL. ±0,25 ANGLES ±2°
REMOVE SHARP CORNERS - CHAMFER OR R0,5 MAX.
INTERNAL RADII 0,5 MAX. SURFACE TEXTURE - √Ra 3,2
THREADS TO BS 3643 6g/6H. DRAWING PRACTICE TO BS 8888

3rd ANGLE PROJECTION

DO NOT SCALE

TITLE	DRAWN BY	DRAWN DATE	SHEET	CHECKED
LOWER BODY SEAL	DW	SEP 15	1 OF 1	SH

RENISHAW MATL R CODE	MATERIAL (ENTER R OR FP CODE TO VIEW EQUIVALENT MATERIAL SPEC USING SUPPLIER PORTAL SITE @ WWW.RENISHAW.COM)
R-2022-0000	ALUMINIUM ALLOY, SELECTED HIGH FINISH - EN 573-3 AW6082-T6.

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GL12 8JR

SCALE U.O.S.	DRAWING No.
2:1	G-5858-7005-01-A